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RESEARCH MEMORANDUM

CALCULATED CONDENSER PERFORMANCE FOR A STEAM-TURBINE

POWER PLANT FOR AIRCRAFT

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SUMMARY

As part of an investigation of the application of nuclear
energy to aircraft, calculations have been made to determine the
effect of several operating conditions on the performance of
condensers for steam-turbine power plants. The analysis covered
a range of turbine-inlet pressures from 1000 to 1800 pounds per
square inch absolute and turbine-outlet pressures from 10 to
200 pounds per square inch absolute for various condenser cooling-
air pressure drops, flight speeds, and altitudes. Some calcula-
tions were made to determine the advisability of using a cooling
fan in conjunction with the steam condenser.

A rough estimate of the total power-plant weight including
propeller but excluding reactor is included along with values of
the ratio of disposable load (load-carrying capacity) to airplane
gross weight for a steam-turbine-powered aircraft at one set of
turbine operating conditions and two flight conditions.

At a turbine-inlet pressure of 1400 pounds per square inch
absolute and a turbine-inlet temperature of 866° F, the minimum
specific condenser weight was 257 pounds per 1000 net thrust
horsepower and the minimum specific condenser frontal area was
16.7 square feet per 1000 net thrust horsepower. These values
occurred at a turbine-outlet pressure of 100 pounds per square
inch absolute, a flight speed of 500 miles per hour, and an
altitude of about 15,000 feet.

INTRODUCTION

One possible method of application of nuclear energy to aircraft
propulsion is the use of a nuclear reactor as the heat source in a
steam-turbine power plant. Aside from reactor considerations, the
condenser, due to its excessive size and internal drag power, presents
an important problem in the use of such a system.

UNCLASSIFIED

The results of an analysis to determine the effect of steam-cycle operating conditions, cooling-air pressure drop, altitude, and flight speed on the frontal area, weight, and internal drag of the condenser are reported. The analysis covers a range of turbine-inlet pressures, turbine-outlet pressures, cooling-air pressure drops, altitudes, and flight speeds.

An estimate of the total power-plant weight, excluding the weight of the nuclear reactor, was made for one set of turbine operating conditions and two flight conditions and was used to calculate the percentage of the gross weight of the airplane that would be available for carrying the reactor and cargo.

Condenser computations were based on an aluminum heat exchanger of the aircraft fin-and-tube type. Heat-dissipation rates and some cooling-air pressure-drop data were obtained from charts supplied by the heat-exchanger manufacturer.

METHODS OF ANALYSIS

The power plant was considered to consist of a nuclear-reactor boiler, a steam turbine, an air-cooled condenser, and the necessary pumps, valves, and piping. The boiler feed pump was assumed to be driven directly by the turbine and the net shaft power delivered to a propeller.

Calculations were made to determine the effect of steam-cycle operating conditions, ratio of cooling-air static-pressure drop to compressible dynamic pressure $(\Delta p/q)$, altitude, and flight speed on condenser size and internal drag power. Some additional calculations were made to determine the effect of a cooling fan on condenser performance.

Calculations were made for two flight conditions to determine what percentage of the gross weight of a steam-turbine-powered airplane would be available for disposable load, that is, for the nuclear reactor and cargo.

The calculations covered a range of turbine-outlet pressures from 10 to 200 pounds per square inch absolute and a range of $\Delta p/q$ from 0.10 to 0.60 at turbine-inlet pressures of 1000, 1400, and 1800 pounds per square inch absolute for a flight speed of 500 miles per hour and an altitude of 30,000 feet. For each combination of turbine-inlet and turbine-outlet pressure, a turbine-inlet temperature was selected that would give saturated steam

(100-percent quality) at the turbine outlet. A range of flight speeds from 100 to 500 miles per hour was investigated at altitudes of sea-level, 15,000, and 30,000 feet for turbine-inlet and turbine-outlet pressures of 1400 and 100 pounds per square inch absolute, respectively.

For all calculations except those involving power-plant-weight estimates, the steam rate was adjusted to give 1000 net shaft horsepower from the turbine with an adiabatic efficiency of 85 percent. The 1000 horsepower was then supplied to a propeller having an efficiency of 85 percent.

Condenser calculations were based on an aircraft fin-and-tube-type heat exchanger manufactured by Harrison Radiator Division, General Motors Corporation having a core weight, including tube headers but excluding inlet and outlet steam tanks, of 15.4 pounds per square foot of core frontal area. Several core configurations for the fin-and-tube-type construction were investigated and the exchanger with the core structure, shown schematically in figure 1, was found to give the best performance. Heat-dissipation rates were determined from charts supplied by the heat-exchanger manufacturer. Cooling-air pressure drops were determined from the manufacturer's charts modified to account for the effects of altitude and higher heat loading.

For a given heat rejection to the cooling air by the condenser and cooling-air pressure drop, the required condenser frontal area and weight and the weight flow of cooling air were determined from the modified charts. The internal drag power of the condenser was then calculated from the change in momentum of the cooling air. The net thrust power was taken as the algebraic difference between the propeller thrust power (product of turbine power and propeller efficiency) and the internal drag power of the condenser. Specific condenser weight and frontal area were then computed from the net thrust power and the weight and frontal area of the condenser.

The calculations of disposable load, which were based on 5000 net shaft horsepower from the turbine, involved the determination of the nacelle drag power and an estimation of the total power-plant weight including propeller, engine mountings, air ducting, and controls. A lift-to-drag ratio of 18 for the airplane without nacelles and a ratio of structural weight to gross weight of 0.4 were assumed. One calculation was made assuming the condenser to be so installed in the wings that no condenser external drag was involved and another calculation was made for the condenser enclosed in a nacelle.

Army standard air (99° F at sea level) was used for all calcu-
lations. Details of the calculations are presented in the appendix.

RESULTS AND DISCUSSION

Steam-cycle performance. - The effect of turbine-outlet pres-
sure on cycle efficiency, steam rate, turbine-inlet temperature,
reactor-heat input, heat rejected by condenser, and turbine-outlet
temperature is shown in figure 2 for a net turbine horsepower of
1000 and a turbine efficiency of 85 percent at turbine-inlet pres-
sures of 1000, 1400, and 1800 pounds per square inch absolute.
Turbine-inlet temperatures were selected to give saturated steam
of 100-percent quality at the turbine outlet.

As the outlet pressure increases and the inlet pressure decreases,
the cycle efficiency decreases; the steam rate, the reactor-heat input,
and the condenser heat rejection increase. The increases in reactor-
heat input and condenser heat rejection are due to the decrease in
cycle efficiency and the attendant increases in steam rate required
to maintain constant turbine output.

Effect of turbine-outlet pressure on condenser performance.
The effect of turbine-outlet pressure on net thrust power, condenser
weight and frontal area, specific condenser weight (lb/1000 net
thrust hp), and specific condenser frontal area (sq ft/1000 net
thrust hp) is shown in figure 3 for turbine-inlet pressures of
1000, 1400, and 1800 pounds per square inch absolute, values of
$\Delta p/q$ of 0.20, 0.40, and 0.60, and 1000 turbine horsepower.

As the outlet pressure is increased from its minimum value of
10 pounds per square inch, the condenser weight and frontal area
show an initial decrease followed by an increase, with the minimum
values occurring at an outlet pressure of about 40 pounds per square
inch absolute. The condenser frontal area and weight are directly
proportional to the heat to be removed by the condenser Q_c and
inversely proportional to the initial temperature difference ΔT_i
between the condensing steam and the entering cooling air. In the
low outlet-pressure range, ΔT_i increases more rapidly than Q_c;
hence, there is an initial decrease in condenser area. Above an
outlet pressure of about 40 pounds per square inch absolute, however,
Q_c increases more rapidly than ΔT_i and the area must also increase.
The required frontal area decreases with increasing inlet pressure
owing to the attendant decrease in heat rejection. (See fig. 2.)

The net thrust power increases with outlet pressure for most combinations of inlet pressure and $\Delta p/q$. The exceptions are at a $\Delta p/q$ of 0.60 at inlet pressures of 1000 and 1400 pounds per square inch absolute where the net thrust power reaches a maximum value and then decreases as the outlet pressure is further increased from its minimum value. (See fig. 3(c).) The changes in net thrust power are due to the combined effects of increased steam temperature and heat rejection on the cooling-air flow and temperature rise and hence on internal drag power (Meredith effect).

Net thrust power increases with increasing turbine-inlet pressure except at high turbine-outlet pressures for a $\Delta p/q$ of 0.20. (See fig. 3(a).) At constant outlet pressure, and hence constant outlet steam temperature, a decrease in inlet pressure increases the heat rejection and thus increases the required condenser size and total cooling-air flow. For most cases, this result means an increase in internal drag power with a consequent decrease in net thrust power. At a $\Delta p/q$ of 0.20 and high outlet pressures, however, the condenser has negative internal drag (thrust) and the increase in cooling-air flow resulting from the decreased turbine-inlet pressure increases this thrust and hence the net power. It may be noted that the propeller thrust horsepower is 850 (0.85×1000), and therefore condenser thrust and drag powers are the difference between values of net thrust power from the data figures and 850; positive values of the difference indicate thrust and negative values indicate drag.

Specific condenser weight and specific condenser frontal area have a minimum point at turbine-outlet pressures between approximately 30 and 100 pounds per square inch absolute for the range of inlet pressures and $\Delta p/q$ investigated. Minimum specific weights and areas occur at the maximum inlet pressure.

Although low turbine-outlet pressures are generally considered desirable in steam work as far as efficiency is concerned, in an aircraft installation low outlet pressures with the attendant low steam temperatures (low initial temperature differences ΔT_i) result in excessive condenser size. The decrease in steam-cycle efficiency attending operation at high outlet pressures is partly compensated for in aircraft installations by the decreased internal drag or, for some cases, by the increased thrust developed by the condenser as a result of the greater heat dissipation. Furthermore, operation at high outlet pressures would be advantageous from the consideration of decreased turbine weight.

Effect of cooling-air pressure drop on condenser performance. -
The variation of net thrust power, condenser weight and frontal area,
and specific condenser weight and frontal area with $\Delta p/q$ is
shown in figure 4 (a cross-plot of fig. 3) for turbine-inlet pres-
sures of 1000, 1400, and 1800 pounds per square inch absolute and
a turbine-outlet pressure of 100 pounds per square inch absolute.

The condenser weight and frontal area decrease with increasing
$\Delta p/q$ inasmuch as the required area is less at the higher pressure
drops. The net thrust horsepower also decreases with increasing
$\Delta p/q$ due to the increase in internal drag power.

The specific condenser weight and frontal area have minimum
values at a $\Delta p/q$ of about 0.30 at all turbine-inlet pressures for
the flight speed and altitude shown. The values of $\Delta p/q$ corre-
sponding to minimum values of specific condenser weight and frontal
area vary somewhat with flight speed and altitude, as will be seen
in a subsequent figure.

Effect of turbine-inlet temperature on condenser performance. -
The variation of net thrust power, condenser weight and frontal area,
and specific condenser weight and frontal area with turbine-inlet tempera-
ture is shown in figure 5. The curves are for a turbine-inlet pres-
sure of 1400 pounds per square inch absolute, a turbine-outlet pres-
sure of 100 pounds per square inch absolute, a $\Delta p/q$ of 0.30, and a
turbine horsepower of 1000. A line a-b is drawn through a tempera-
ture of 866° F, the turbine-inlet temperature that will give satu-
rated steam (100-percent quality) at the turbine outlet for the
turbine-inlet and turbine-outlet pressures considered. Any tempera-
ture above 866° F will result in superheated steam at the turbine
outlet.

Superheating to turbine-inlet temperatures higher than those
required to give saturated steam at the turbine outlet results in
an increase in steam-cycle efficiency and in work available per
pound of steam with the result that for constant turbine horse-
power the steam flow is decreased. Although the heat rejected by
the condenser per pound of steam increases, the total heat that
must be removed by the condenser is decreased. Also, the higher
turbine-outlet (condenser-inlet) steam temperature increases the
initial temperature difference between the steam and the cooling
air. The reduced heat rejection and the higher initial temperature
difference act to decrease the condenser frontal area and weight.
The foregoing effects are offset to some extent by the fact that
the heat-transfer coefficient for cooling superheated steam is con-
siderably smaller than for condensing steam with the result that

the surface area and, hence, frontal area required for cooling the
steam is proportionately larger. A reduction in specific condenser
weight and frontal area of about 8 percent is obtained by increasing
the turbine-inlet temperature from 866° to 1600° F.

These results were obtained assuming the same exchanger core
structure to be used for the cooling as for the condensing process.
A somewhat greater reduction in specific condenser frontal area
and a slightly greater reduction in specific condenser weight with
increasing turbine-inlet temperature may possibly be obtained by
using an exchanger specifically designed for the steam-cooling
process.

Effect of flight speed and altitude on condenser performance. -
The effect of flight speed on net thrust horsepower, specific con-
denser weight, and specific condenser frontal area for various
condenser weights and frontal areas at altitudes of sea-level,
15,000, and 30,000 feet is shown in figure 6. The turbine-inlet
pressure is 1400 pounds per square inch absolute, the turbine-
outlet pressure is 100 pounds per square inch absolute, the
turbine-inlet temperature is 866° F, and the turbine horsepower
is 1000. Also shown on these curves are lines of constant $\Delta p/q$.
The lines of required pressure drop equal to maximum available
pressure drop mark the limiting flight speeds below which the
condensers will not dissipate the required amount of heat.

In general, for constant altitude and condenser weight and
frontal area, the net thrust power increases and the specific
condenser weight and frontal area decrease with increasing flight
speed. The effect of flight speed decreases as the altitude decreases
and at sea level the curves for net thrust power and specific weight
and frontal area are relatively insensitive to changes in flight
speed. The highest net thrust powers are obtained with the largest
condensers at all altitudes because the required pressure drops
and, hence, the internal drag power losses are less. The condenser
weight and frontal area for minimum specific weight and frontal
area increases slightly with increasing altitude; however, the
13.0-square-foot condenser is approximately the optimum, on the
basis of specific weight, for the range of altitudes and flight
speeds investigated. The curve for the 9.7-square-foot condenser
was omitted from figure 6(c) (altitude, 30,000 ft) because of the
extremely high specific condenser weight and specific frontal area.

Figure 6 shows, as previously mentioned, that the values of
$\Delta p/q$ corresponding to minimum values of specific condenser weight
and frontal area vary with flight speed and altitude. For constant

altitude, the value of $\Delta p/q$ corresponding to minimum specific con-
denser weight and frontal area tends to increase as flight speed is
decreased. Comparison of figures 6(a), 6(b), and 6(c) shows that
for constant flight speed the value of $\Delta p/q$ for minimum specific
weight and area increases as the altitude is increased.

The variation of net thrust horsepower with flight speed and
altitude for the condenser weighing 200 pounds and having a frontal
area of 13.0 square feet is shown as a three-dimensional plot in
figure 7. The line a-b indicates the combinations of altitude
and flight speed for which the required pressure drop equals the
maximum available pressure drop. At sea level, the minimum speed
is about 185 miles per hour; the power plant would therefore have
to be operated partly noncondensing in take-off until this minimum
speed is reached.

The maximum point on the surface c-d-e-f indicates the speed
and altitude at which maximum net thrust power and hence, minimum
specific weight and minimum specific frontal area occur. A minimum
specific weight of 257 pounds and a minimum specific frontal area
of 16.7 square feet occur at an altitude of about 15,000 feet and
a flight speed of 500 miles per hour. This frontal area is large
compared to that required for a radiator for a conventional liquid-
cooled aircraft engine (about 1.5 sq ft/1000 hp).

Effect of cooling fan on condenser performance. - The effect
of a cooling fan on condenser performance is shown in figure 8
where net thrust horsepower, specific condenser weight, and specific
condenser frontal area are plotted against $\Delta P_f/q$ (ratio of total
pressure rise across the fan to compressible dynamic pressure at
the assumed altitude and speed) for various condenser weights and
frontal areas at a flight speed of 500 miles per hour and an alti-
tude of 30,000 feet. The line $\Delta P_f/q = 0$ represents the case
where no fan is used.

For each of the condensers considered, the net thrust power
has a maximum value and the specific condenser weight and area
have minimum values when $\Delta P_f/q$ is between 0.5 and 1.0. The
curves indicate only a small improvement in performance by the
addition of a fan except for the 9.7-square-foot condenser.
Although the improvement in performance of this condenser is large,
its best performance is considerably poorer than the larger con-
densers with no fan.

The effect of a fan on condenser performance is shown in fig-
ure 9 for a 19.5-square-foot condenser at three altitudes at a
flight speed of 500 miles per hour and at an altitude of 30,000 feet
and a flight speed of 300 miles per hour. Figure 9 shows that the
improvements in performance obtainable with a cooling fan are even
smaller at the lower altitudes and only slightly greater at the
lower flight speed.

The maximum decrease in specific weight and specific frontal
area of the condenser with the most effective size (13.0 sq ft)
that can be obtained by use of a fan is about 11 percent.
(See fig. 8.) In view of the small gains in condenser performance,
the additional weight of the fan, and the complexities of the
installation, a fan is probably undesirable for this type of
system.

Effect of turbine-outlet pressure on over-all efficiency. -
The variation of over-all efficiency, defined as the dimensionless
ratio of net thrust power minus nacelle drag power to reactor-heat
input, is probably of greater importance than the previously dis-
cussed variation of specific condenser weight and frontal area.
If the reactor weight is the principal consideration, then with
the reactor operating at its maximum heat-release rate, maximum
net thrust power per unit weight of the system will be obtained
at maximum over-all efficiency.

The effect of turbine-outlet pressure on over-all efficiency
is shown in figure 10 for various turbine-inlet pressures and
values of $\Delta p/q$. The over-all efficiency decreases with increasing
outlet pressure except at high values of $\Delta p/q$, where it has a
maximum at outlet pressures between 40 and 80 pounds per square
inch absolute. As previously mentioned, the most effective
operating outlet pressure from considerations of specific con-
denser weight and frontal area is between approximately 30 and
100 pounds per square inch absolute. (See fig. 3.) The curves
of over-all efficiency and specific condenser weight and frontal
area at values of $\Delta p/q$ of 0.20 and 0.40 are relatively flat in
this region of turbine-outlet pressure; hence, it appears that the
most desirable operating conditions from considerations of optimum
utilization of the reactor may occur close to the optimum operating
conditions for the condenser.

Because of the relative effects of condenser internal and
external drag, the over-all efficiency (at constant values of
turbine-inlet and turbine-outlet conditions) passes through a
maximum at some value of $\Delta p/q$, which depends on flight speed

and altitude. For the flight conditions shown, the maximum values
of over-all efficiency occur at a value of $\Delta p/q$ of about 0.20 for
all turbine-inlet and turbine-outlet pressures.

Power-plant-weight estimates. - Weight estimates indicate that
for a turbine operating at an inlet pressure of 1400 pounds per
square inch absolute, an outlet pressure of 100 pounds per square
inch absolute, an inlet temperature of 866° F, and a power output
of 5000 horsepower the total power-plant weight including propeller
but excluding reactor and working fluid would be 5460 pounds at a
flight speed of 500 miles per hour and an altitude of 30,000 feet.
(See the appendix for a discussion of the weight breakdown.) This
weight would correspond to specific weights of 1.09 pounds per
turbine horsepower, 1.59 pounds per net thrust horsepower with the
condenser submerged in the wings (no external nacelle drag), and
2.55 pounds per net thrust horsepower with the condenser in a
nacelle. At a flight speed of 300 miles per hour and an altitude
of 15,000 feet, the power-plant weight would be 5870 pounds
(owing to a heavier propeller) and the corresponding specific
weights would be 1.17, 1.74, and 1.97 pounds per horsepower,
respectively.

For the condenser enclosed in a nacelle, the ratio of dispos-
able load to gross weight of the airplane would be 0.41 for a
flight speed of 500 miles per hour and an altitude of 30,000 feet.
If the condenser could be so installed in the wings as to eliminate
external drag, this value could be raised to 0.48. In other words,
a weight-carrying capacity equal to 41 to 48 percent of the gross
weight of the airplane would be available for a nuclear reactor,
working fluid, and cargo; or conversely, the gross weight of an
airplane with a nuclear-energy steam-turbine power plant would be
about 2 to $2\frac{1}{2}$ times the weight of the reactor, working fluid, and
cargo. ·

For the same condenser and operating conditions but at a flight
speed of 300 miles per hour and an altitude of 15,000 feet, the
values of the ratio of disposable load to gross weight for the cases
of the condenser in a nacelle and the condenser submerged would be
0.51 and 0.52, respectively.

SUMMARY OF RESULTS

The results of calculations of the performance of condensers
for a nuclear-energy steam-turbine power plant for aircraft may be
summarized as follows:

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1. Minimum specific condenser weights and specific frontal areas occurred at turbine-outlet pressures between approximately 30 and 100 pounds per square inch absolute for inlet pressures of 1000, 1400, and 1800 pounds per square inch absolute and cooling-air pressure drops of 20 to 60 percent of the compressible dynamic pressure.

2. At a turbine-inlet pressure of 1400 pounds per square inch absolute and a turbine-inlet temperature of 866° F, the minimum specific condenser weight was 257 pounds per 1000 net thrust horse-power and the minimum specific condenser frontal area was 16:7 square feet per 1000 net thrust horsepower. These values occurred at a turbine-outlet pressure of 100 pounds per square inch absolute, a flight speed of 500 miles per hour, and an altitude of about 15,000 feet.

3. Relatively small improvement in condenser performance can be obtained by increasing the turbine-inlet temperature above that required to give saturated steam at the turbine outlet.

4. A decrease in specific condenser weight and frontal area of about 11 percent may be obtained at an altitude of 30,000 feet and an airplane velocity of 500 miles per hour by placing a cooling fan ahead of the condenser. The greatest gains in performance with a fan were obtained at the highest altitude investigated. In view of the additional weight of the fan and the installation complexities, the improvements in performance obtained by use of the fan are probably insignificant.

5. A weight estimate based on a turbine output of 5000 horse-power at a flight speed of 500 miles per hour and an altitude of 30,000 feet indicated that the specific weights of the installed power plant excluding the reactor would be 1.09 pounds per turbine horsepower, 1.59 pounds per net thrust horsepower with condenser submerged in the wings (no external condenser drag), and 2.55 pounds per net thrust horsepower with condenser enclosed in a nacelle. Calculations based on this weight estimate indicate that a weight-carrying capacity equal to 41 percent (condenser in nacelle) to 48 percent (condenser in wing) of the gross weight of a steam-turbine-powered aircraft would be available for carrying the nuclear reactor and cargo.

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APPENDIX - DETAILS OF METHOD OF CALCULATION

Steam-cycle calculations. - The cycle is shown on enthalpy-entropy (H - S) coordinates in figure 11. A pump raises the water pressure from the turbine-outlet pressure P_0 to the turbine-inlet pressure P_1 along line a-b in figure 11. The water is warmed, evaporated, and superheated in the boiler along line b-c to the turbine-inlet temperature (point c). Steam at the conditions represented by point c enters the turbine and expands to saturation at the turbine-outlet pressure (point d). A condenser removes the latent heat of the steam and discharges it as saturated liquid at point a. Pressure drops of the working fluid through the boiler and the condenser were neglected. The enthalpy (and superheat) at point c was determined by trial and error and had a value such that

$$\frac{H_c - H_d}{H_c - H_d{}'} = 0.85 \tag{1}$$

where the subscripts refer to points on figure 11. That is, the adiabatic efficiency of the turbine was 85 percent. The pumping work per pound of steam was taken as $(P_1 - P_0)v$ (where v is the specific volume of the saturated liquid at P_0).

For all calculations, the steam rate was adjusted to give 1000 shaft horsepower after the deduction of pumping power. The required steam rate W_s in pounds per second for 1000 net shaft horsepower was therefore obtained from the following relation:

$$\left[778 \, (H_c - H_d) - (P_1 - P_0) \, v\right] \frac{W_s}{550} = 1000 \tag{2}$$

where $(H_c - H_d)$ is in Btu per pound, $(P_1 - P_0)$ is in pounds per square foot, and v is in cubic feet per pound.

The reactor-heat input Q_r (Btu/sec), the heat rejected to the condenser Q_c (Btu/sec), and the cycle efficiency η_c were obtained by the following relations:

$$Q_r = W_s \left[(H_c - H_a) - (P_1 - P_0) \frac{v}{778}\right] \tag{3}$$

$$Q_c = W_s \, (H_d - H_a) \tag{4}$$

$$\eta_c = \frac{(H_c - H_d) - (P_1 - P_0) \frac{v}{778}}{(H_c - H_a) - (P_1 - P_0) \frac{v}{778}} \tag{5}$$

The properties of the steam for these calculations were obtained from reference 1.

Condenser cooling-air pressure drop. - Charts of heat dissipation and cooling-air static-pressure drop against cooling-air flow for the condenser were supplied by the heat-exchanger manufacturer. The investigations from which the data for these curves were obtained were made at sea-level entrance conditions of cooling-air pressure and temperature and with an initial temperature difference ΔT_i between the condensing steam and cooling air of approximately $100°$ F. The heat dissipations given by the charts are valid for all entrance conditions and initial temperature differences. The variation of heat dissipation in Btu per minute per $100°$ F of initial temperature difference with cooling-air flow in pounds per minute is shown in figure 12 for a condenser having a frontal area of 1 square foot. The pressure drop required for a given flow of cooling air, however, may vary considerably with altitude, flight speed, and initial temperature difference making it necessary to modify the experimental curve in order to account for the effect of these variables.

The experimental curves were modified by calculating values of the cooling-air static-pressure drop across the condenser $\sigma\Delta p$ (product of the ratio σ of cooling-air entrance density to NACA standard sea-level density and the static-pressure drop Δp) for various altitudes and heat loadings. The quantity $\sigma\Delta p$ was taken as the sum of: (1) entrance loss; (2) velocity-profile loss; (3) vena-contracta loss; (4) friction loss; (5) heat-exchange or momentum loss; and (6) exit loss. Density changes at the entrance and exit sections were assumed to be negligible and an average density was used to calculate the friction loss. With the assumption that the air-flow passages between the elongated tubes and fins were rectangular channels (fig. 1) having an effective diameter equal to four times the cross-sectional area divided by the perimeter, the variation of friction factor with Reynolds number was calculated using the cooling-air pressure drops and corresponding air flows from the manufacturer's experimental sea-level curves. These friction factors together with velocity and density changes of the cooling air in the condenser resulting from variation in altitude and heat loading were then used to calculate the corresponding pressure drops. The calculations were limited to turbulent flow (approximate range of Reynolds number, 2000 to 20,000) and to Mach numbers in the condenser of less than 0.5.

The variation of $\sigma\Delta p$ with cooling-air flow is shown in figure 13. Curve A is the manufacturer's experimental curve for sea-level entrance conditions and an initial temperature difference of 100° F. Curves B, C, D, and E are representative calculated curves for an altitude of 30,000 feet, a flight speed of 500 miles per hour, and initial temperature differences of 100°, 200°, 300°, and 400° F, respectively.

Condenser weight, frontal area, and internal drag. - A schematic diagram of the condenser enclosed in a nacelle is shown in figure 14(a). Army standard air was assumed at station 0 ahead of the nacelle. The total temperature at the face of the condenser, station 1, was calculated from the expression

$$T_1 = t_0 + \frac{V_0^2}{2gJc_p} \qquad (6)$$

where

T_1 total temperature at condenser face, $^\circ$R

t_0 ambient-air temperature, $^\circ$R

V_0 flight speed, ft/sec

g acceleration due to gravity, 32.2 ft/sec^2

J mechanical equivalent of heat, 778 ft-lb/Btu

c_p specific heat of air at constant pressure, Btu/(lb)($^\circ$F)

The static pressure at the face of the condenser was taken as

$$p_1 = p_0 \left\{ \left[\left(1 + \frac{V_0^2 - V_1^2}{2gJc_p t_0} \right)^{\frac{\gamma}{\gamma-1}} - 1 \right] \epsilon_r + 1 \right\} \qquad (7)$$

where

p_1 static pressure at condenser face, in. Hg absolute

p_0 ambient-air pressure, in. Hg absolute

V_1 velocity at condenser face, ft/sec

γ ratio of specific heats of air

ϵ_r diffuser pressure-rise recovery factor, (assumed to be 0.90)

The initial temperature difference ΔT_1 between the steam and the cooling air was taken as $T_s - T_1$, where T_s is the temperature of the steam in the condenser.

The relation between condenser frontal area, heat dissipation rate, initial temperature difference, and heat removed from the steam by the condenser is given by the following expression:

$$A = \frac{60 \times 100 \; Q_c}{H_r \; \Delta T_1} \tag{8}$$

where

A condenser frontal area, sq ft

Q_c heat removed from steam by condenser, Btu/sec

H_r heat-dissipation rate, $(Btu)/(min)(100^\circ\ F\ \Delta T_1)(sq\ ft\ frontal\ area)$

The quantity H_r is a function of the cooling-air flow (fig. 12), which is a function of the pressure drop (fig. 13); hence, for given values of Q_c, ΔT_1, and static-pressure drop $\sigma\Delta p$, a value of H_r and therefore a condenser frontal area may be determined. Also, if the condenser frontal area A is known and Q_c and ΔT_1 are given, a value of H_r can be calculated from equation (8) and the required cooling-air flow and pressure drop determined from figures 12 and 13. Inasmuch as the air flow given in figures 12 and 13 is for a 1-square-foot section, the air flow as obtained from these figures must be multiplied by the total frontal area in order to obtain a total weight flow of cooling air.

The temperature rise of the cooling air in passing through the condenser ΔT_c and the total temperature T_2 at the condenser exit (station 2, fig. 14(a)) are given by

$$T_2 = T_1 + \Delta T_c = T_1 + \frac{Q_c}{W \; c_p} \tag{9}$$

where W is the cooling-air flow in pounds per second. The corresponding static temperature t_2 is given by

$$t_2 = T_2 - \frac{V_2{}^2}{2gJc_p} \qquad (10)$$

where V_2, the velocity of the cooling air at station 2, is obtained from the continuity equation. Thus

$$V_2 = \frac{WR\, t_2}{p_2\, A} \qquad (11)$$

where

R   gas constant for air, ft-lb/(lb)($^\circ$F)

p_2 condenser-outlet static pressure, lb/sq ft absolute

The pressure p_2 was taken as the static pressure at station 1 minus the cooling-air static-pressure drop. The assumption is made in equation (11) that the cross-sectional area at station 2 is the same as the condenser frontal area. Equations (10) and (11) can be combined to give a quadratic equation for t_2 in terms of the known quantities T_2, p_2, W, and A. The velocity at the exit (station 3) is then

$$V_3 = C \sqrt{2gJc_p\, t_2 \left[1 - \left(\frac{p_0}{p_2} \right)^{\frac{\gamma-1}{\gamma}} \right] + V_2{}^2} \qquad (12)$$

where C is an over-all velocity coefficient having an assumed value of 0.96 and the pressures are in inches of mercury absolute.

In the present study, negligible error was introduced by substituting T_2 for t_2 in equations (11) and (12) in order to simplify the computations.

The internal drag horsepower hp_d is

$$hp_d = \frac{WV_0\, (V_0 - V_3)}{550\, g} \qquad (13)$$

The effect of a change in internal drag power is represented through its effect on the net thrust horsepower hp_n, which is defined as

$$hp_n = \eta_p\, hp_t - hp_d \qquad (14)$$

where

hp_t turbine-shaft power (constant at 1000 hp)

η_p propeller efficiency (constant at 0.85)

Effect of turbine-inlet temperature. - In these calculations turbine-inlet temperatures above those required to give saturated steam at the turbine outlet were investigated. The cycle is represented in figure 11 by the path a-b-e-f-a. For this case the condenser must cool steam from point f to point d in addition to the condensing process from point d to point a. Inasmuch as the over-all heat-transfer ccefficient for cooling superheated steam is considerably lower than for condensing steam, the heat-dissipation curve (fig. 12) could not be used to determine the total required frontal area. The size of the heat exchanger required to condense the steam was determined by the method previously outlined and an over-all heat-transfer coefficient based on the effective-air-side surface area was calculated and used to determine the additional area required to cool the steam from point f to point d (fig. 11).

Calculation of the over-all heat-transfer coefficient U_2 for cooling superheated steam involved several steps. The over-all heat-transfer coefficient for condensing steam U_1 was first determined from figure 12. The film coefficient on the steam side $h_{s,1}$ was then calculated from equation (19), reference 2 (p. 269), for film-type condensation on vertical surfaces. When the resistance of the tube wall to heat flow is assumed to be negligible, the air-side film coefficient h_a may then be calculated from the relation

$$\frac{1}{U_1} = \frac{1}{rh_{s,1}} + \frac{1}{h_a} \tag{15}$$

where r is the ratio of steam-side surface area to effective-air-side surface area. A steam-side film coefficient for cooling steam $h_{s,2}$ was then determined by the method given in reference 3 and was used in conjunction with h_a from equation (15) in order to calculate the over-all heat-transfer coefficient for cooling steam U_2:

$$\frac{1}{U_2} = \frac{1}{rh_{s,2}} + \frac{1}{h_a} \tag{16}$$

The remainder of the calculation for internal drag power and net thrust power was the same as that outlined for the straight condensing case.

Condenser and cooling fan. - For these calculations, the fan was assumed to be mounted at the face of the condenser, as shown in figure 14(b). The total-temperature rise across the fan ΔT_f was calculated from the expression

$$\Delta T_f = \frac{T_1}{\eta_f}\left[\left(\frac{P_{1,a}}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \qquad (17)$$

where

T_1 total temperature immediately ahead of fan, °R (calculated from equation (6))

η_f adiabatic fan efficiency (assumed to be 0.85)

P_1 total pressure immediately ahead of fan, in. Hg absolute

$P_{1,a}$ total pressure at condenser face, in. Hg absolute

Calculations were made for a range of values of $\Delta P_f/q$ (ratio of fan total-pressure rise to free-stream compressible dynamic pressure). The horsepower required to drive the fan hp_f was calculated from the expression

$$hp_f = \frac{WJc_p}{550}\Delta T_f \qquad (18)$$

The internal drag power was calculated from equation (13).

The turbine and fan were assumed to be on the same shaft and the turbine power in excess of that required to drive the fan was assumed to be transmitted to the propeller. The expression for net thrust horsepower then becomes

$$hp_n = \eta_p (hp_t - hp_f) - hp_d \qquad (19)$$

Power-plant weight estimate. - Preliminary design calculations were made for a steam turbine delivering 5000 shaft horsepower at an inlet pressure of 1400 pounds per square inch absolute, an inlet temperature of 866° F, and an outlet pressure of 100 pounds per square inch absolute. From the pitch diameters and the number of rotor disks, an estimate was made of rotor and stator weights by assuming that these weights varied as the square of the diameter

and using the weight and pitch diameter of a current aircraft rotor and stator as a standard. Based on stress considerations, the total turbine weight was then increased to allow for the heavy casing required at the high operating pressure.

A condenser with a frontal area of 13 square feet and a weight of 200 pounds, the performance of which is shown in figure 6, was used for this weight estimate. Inasmuch as all previous calculations, including those made for figure 6, were based on 1000 horsepower from the steam turbine, it was necessary to multiply this weight of 200 pounds by 5 to obtain the proper value for a power output of 5000 turbine horsepower.

A boiler feed-pump weight of 200 pounds was considered to be sufficiently high, inasmuch as aircraft-type fuel pumps of the required capacity operating at pressures up to 500 to 600 pounds per square inch and weighing about 50 pounds are now available.

The weight of gearing between the turbine and the propeller was assumed to be 0.2 pound per shaft horsepower, a value consistent with reduction-gear weights of present turbine-propeller engines.

The propeller weight is a scaled value based on the assumption that the weight varies with shaft power, altitude, and flight speed and using the weight and power absorption of a typical aircraft propeller as a base.

A breakdown of the engine weight W_e in pounds (exclusive of reactor and working fluid) is as follows:

Turbine 1000
Condenser core 1000
Propeller (500 mph, 30,000 ft) 1360
Boiler feed pump 200
Piping, valves, fittings, etc. 400
Reducting gearing 1000
Air ducting 200
Engine mountings 200
Controls 100
Total weight 5460

The gross weight W_g of the airplane in pounds was calculated from the expression

$$W_g = \frac{550}{V_0} \frac{L}{D} (\eta_p \, hp_t - hp_d - hp_{nac}) \qquad (20)$$

where

L/D   lift-drag ratio of airplane without nacelles (assumed to be 18)

hp_{nac} external drag power of nacelle, hp

V_0 flight speed, ft/sec

The external drag power of the nacelle was calculated as follows:

$$hp_{nac} = \frac{C_D}{1100\ g}\ \rho_0\ V_0^3\ A_{nac} \tag{21}$$

where

C_D nacelle drag coefficient (assumed to be 0.0657 at 500 mph and
          30,000 ft)

ρ_0 density of ambient air, lb/cu ft

A_{nac} nacelle frontal area, sq ft (assumed to be 1.05 × condenser
          frontal area)

The disposable load W_d available for nuclear reactor, working
fluid, and cargo was then

$$W_d = W_g - W_{st} - W_e \tag{22}$$

where

W_{st} structure weight, lb (assumed to be 40 percent of gross weight)

W_e power-plant weight, lb

The following sample calculations of the quantity W_d/W_g and
specific power-plant weights are given for a flight speed of 500 miles
per hour and an altitude of 30,000 feet: The condenser frontal area
is 13 × 5 (65) square feet and the corresponding net thrust power
($\eta_p\ hp_t - hp_d$) from figure 6(c) is 688 × 5 (3440) horsepower for
5000 turbine horsepower.

$$A_{nac} = 1.05 \times 65 = 68.25 \text{ sq ft}$$

$$hp_{nac} = \frac{0.0657}{1100 \times 32.2} \times 0.02606 \times 733^3 \times 68.25 = 1300 \text{ hp}$$

$$hp_n - hp_{nac} = 3440 - 1300 = 2140 \text{ hp}$$

$$W_g = 18 \times 2140 \times \frac{550}{733} = 28,900 \text{ lb}$$

$$W_{st} = 0.4 \times 28,900 = 11,560 \text{ lb}$$

$$W_d = 28,900 - 11,560 - 5460 = 11,880 \text{ lb}$$

$$\frac{W_d}{W_g} = \frac{11,880}{28,900} = 0.41$$

For the case with the condenser submerged in the wing $(hp_{nac} = 0)$, W_d/W_g is found to be 0.48.

Specific weights of the power plant on the bases of (a) turbine power, (b) net thrust power, and (c) net thrust power minus nacelle drag power are:

(a) pounds per turbine horsepower $= \dfrac{5460}{5000} = 1.09$

(b) pounds per net thrust horsepower $= \dfrac{5460}{3440} = 1.59$

(c) pounds per net thrust horsepower minus nacelle drag

horsepower $= \dfrac{5460}{2140} = 2.55$

At a flight speed of 300 miles per hour and an altitude of 15,000 feet, the propeller weight is 1770 pounds and the corresponding power-plant weight is 5870 pounds. The values of W_d/W_g for these flight conditions are 0.51 with the condenser in a nacelle and 0.52 with the condenser submerged in the wing.

The specific weights at 300 miles per hour and 15,000 feet based on turbine power, net thrust power, and net thrust power minus nacelle drag power are 1.17, 1.74, and 1.97 pounds per horsepower, respectively.

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    erties of Steam. John Wiley & Sons, Inc., 1936.

2. McAdams, William H.: Heat Transmission. McGraw-Hill Book Co.,
    Inc., 2d ed., 1942.

3. Norris, R. H., and Streid, D. D.: Laminar-Flow Heat-Transfer
    Coefficients for Ducts. Am. Soc. Mech. Engrs. Trans., vol. 62,
    no. 6, Aug. 1940, pp. 525-533.

Steam flow
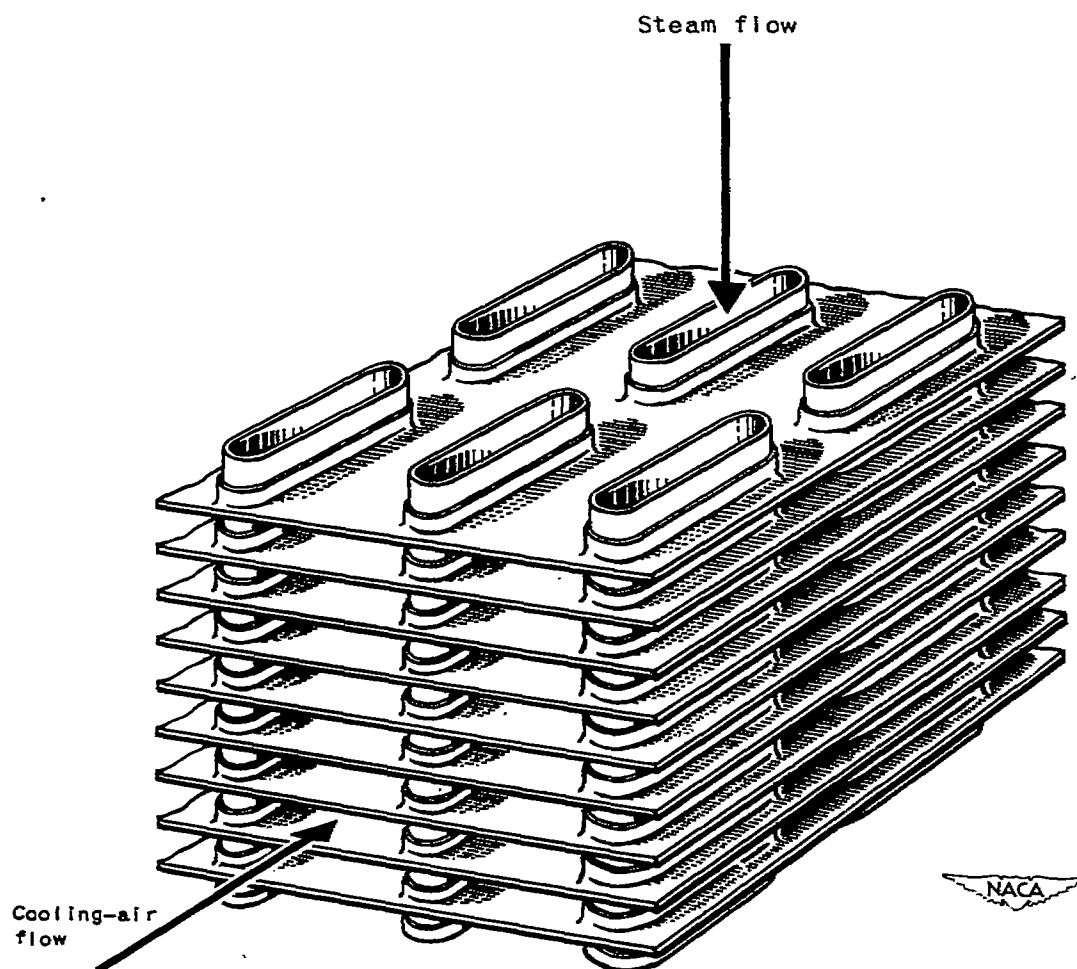
Cooling-air
flow

Dimensions of a 1-square-foot section

Length (steam-flow direction), in.	12
Width (no-flow direction), in.	12
Depth (cooling-air-flow direction), in.	8.75
Fins per in.	11
Outside tube dimensions, in.	1.215 X 0.084
Tube rows (cooling-air-flow direction)	6
Distance between tube center lines (no-flow direction), in.	0.406

Figure 1. — Schematic diagram of condenser-core structure.
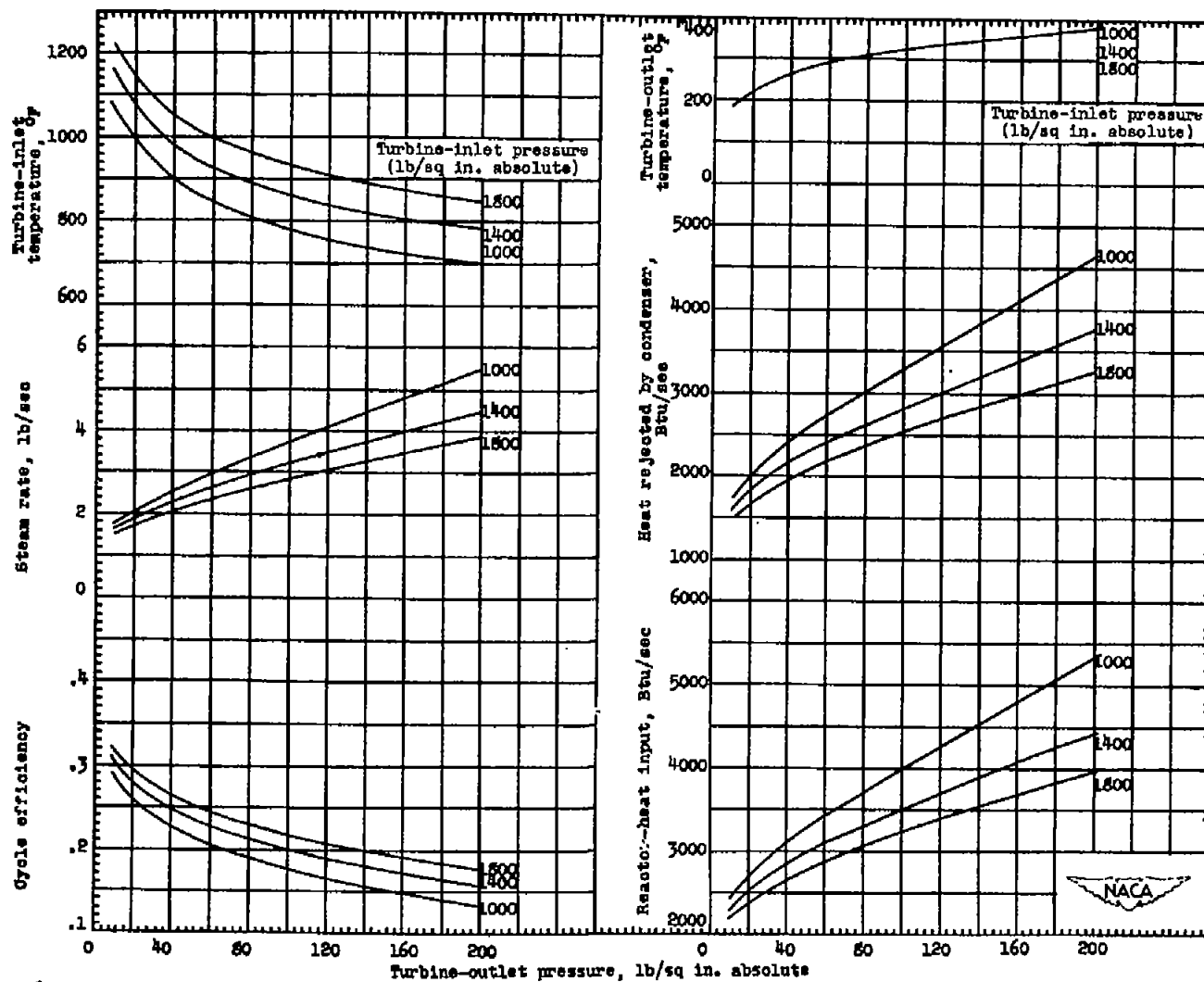
Figure 2. — Variation of cycle efficiency, steam rate, turbine-inlet temperature, reactor-heat input, heat rejected by condenser, and turbine-outlet temperature with turbine-outlet pressure for three turbine-inlet pressures. Turbine power, 1000 horsepower; turbine efficiency, 0.85; saturated steam at turbine outlet.
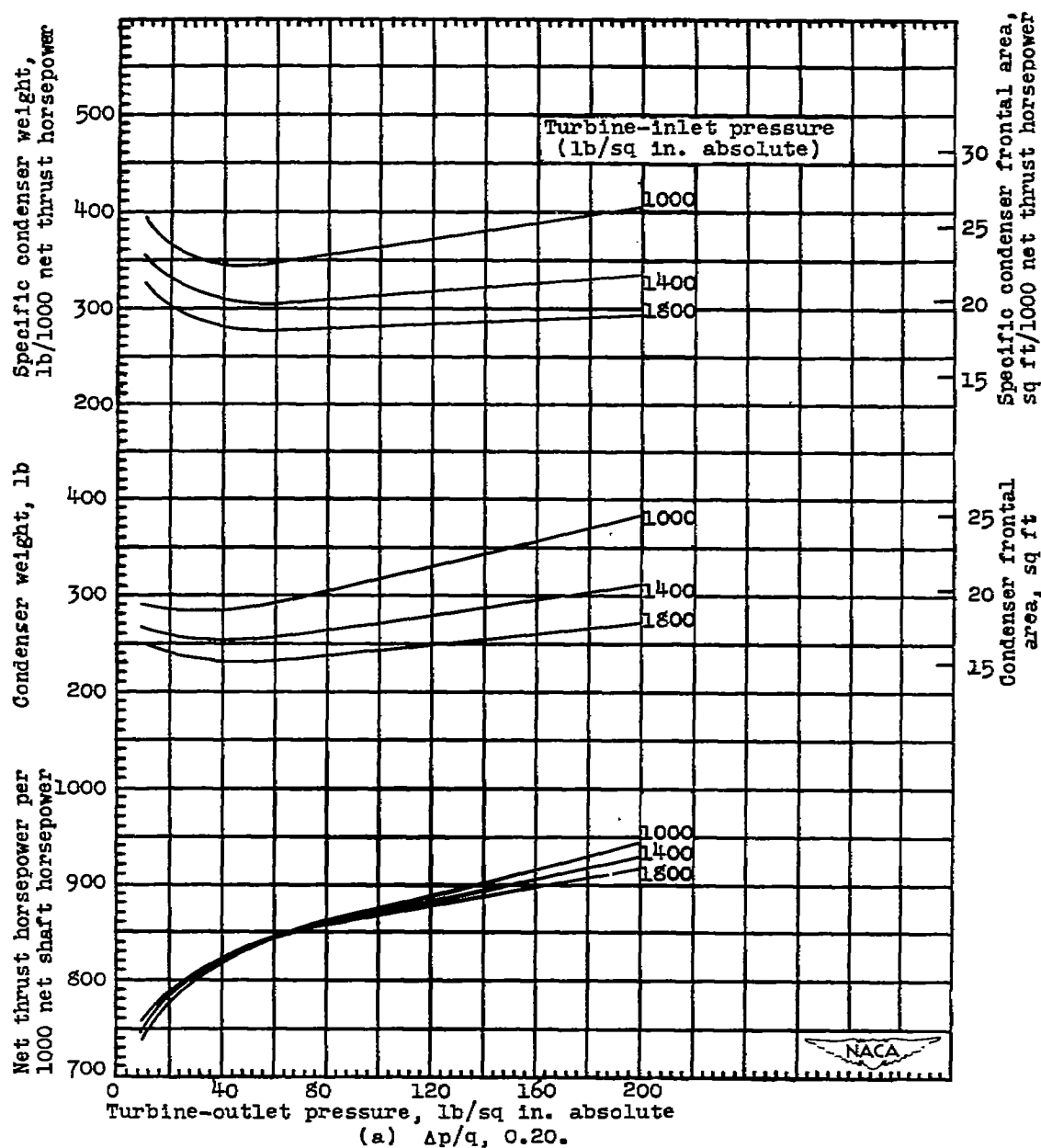
Figure 3. — Variation of net thrust horsepower, condenser weight and
frontal area, and specific condenser weight and frontal area with
turbine-outlet pressure for three turbine-inlet pressures. Flight
speed, 500 miles per hour; altitude, 30,000 feet; turbine power,
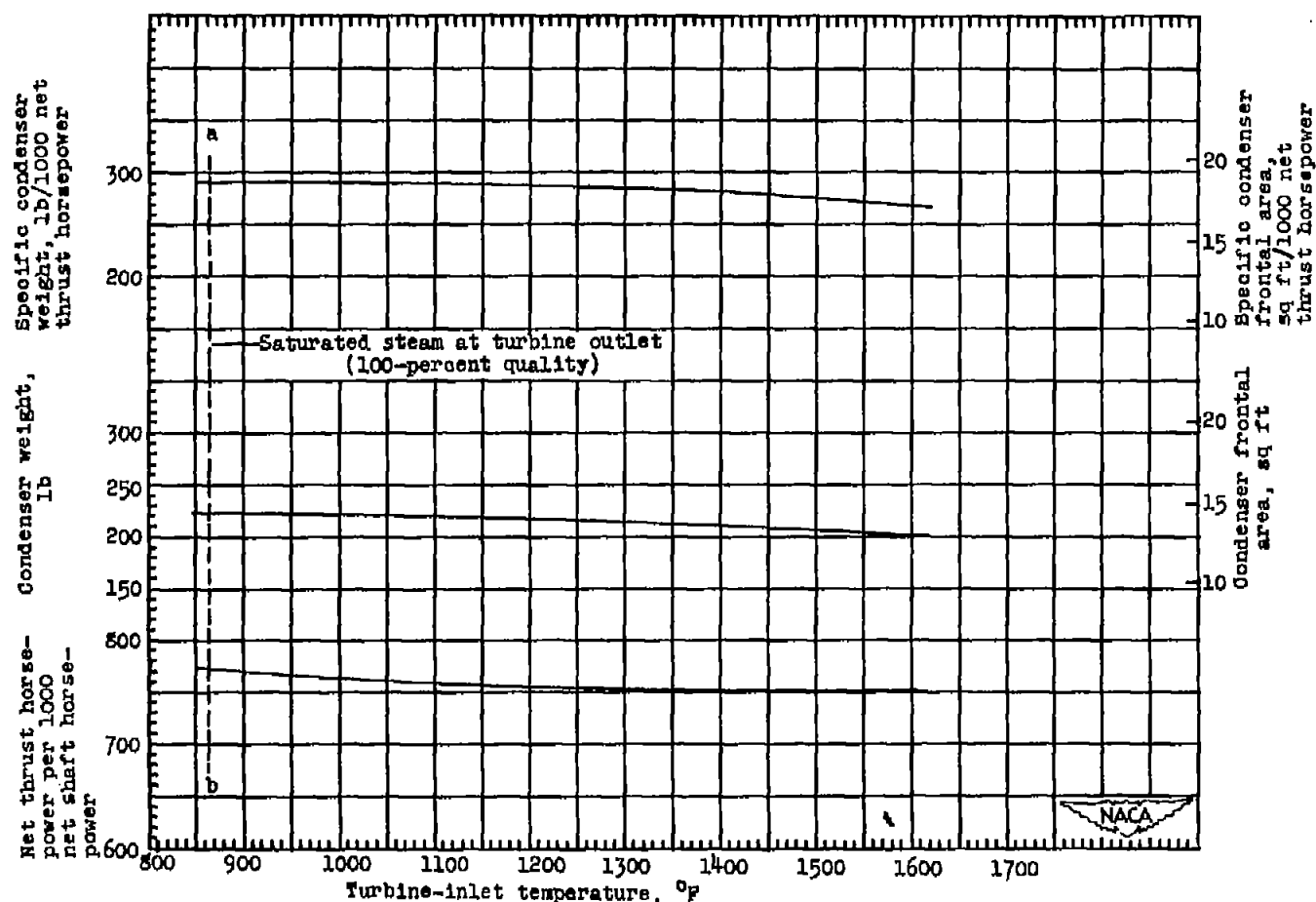1000 horsepower; turbine and propeller efficiencies, 0.85; saturated
steam at turbine outlet.
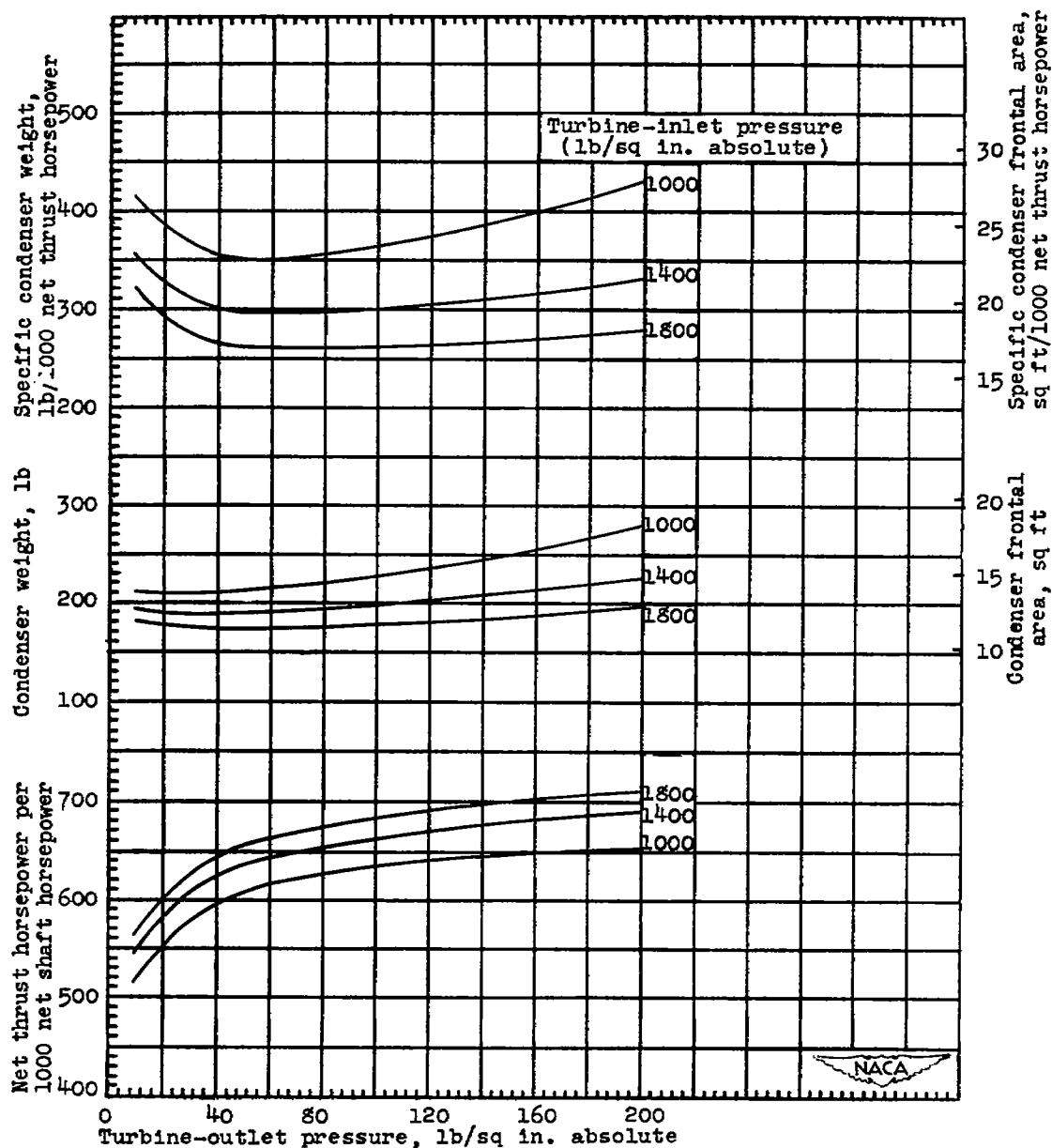
(b) Δp/q, 0.40.

Figure 3. – Continued. Variation of net thrust horsepower, condenser
weight and frontal area, and specific condenser weight and frontal
area with turbine–outlet pressure for three turbine–inlet pressures.
Flight speed, 500 miles per hour; altitude, 30,000 feet; turbine
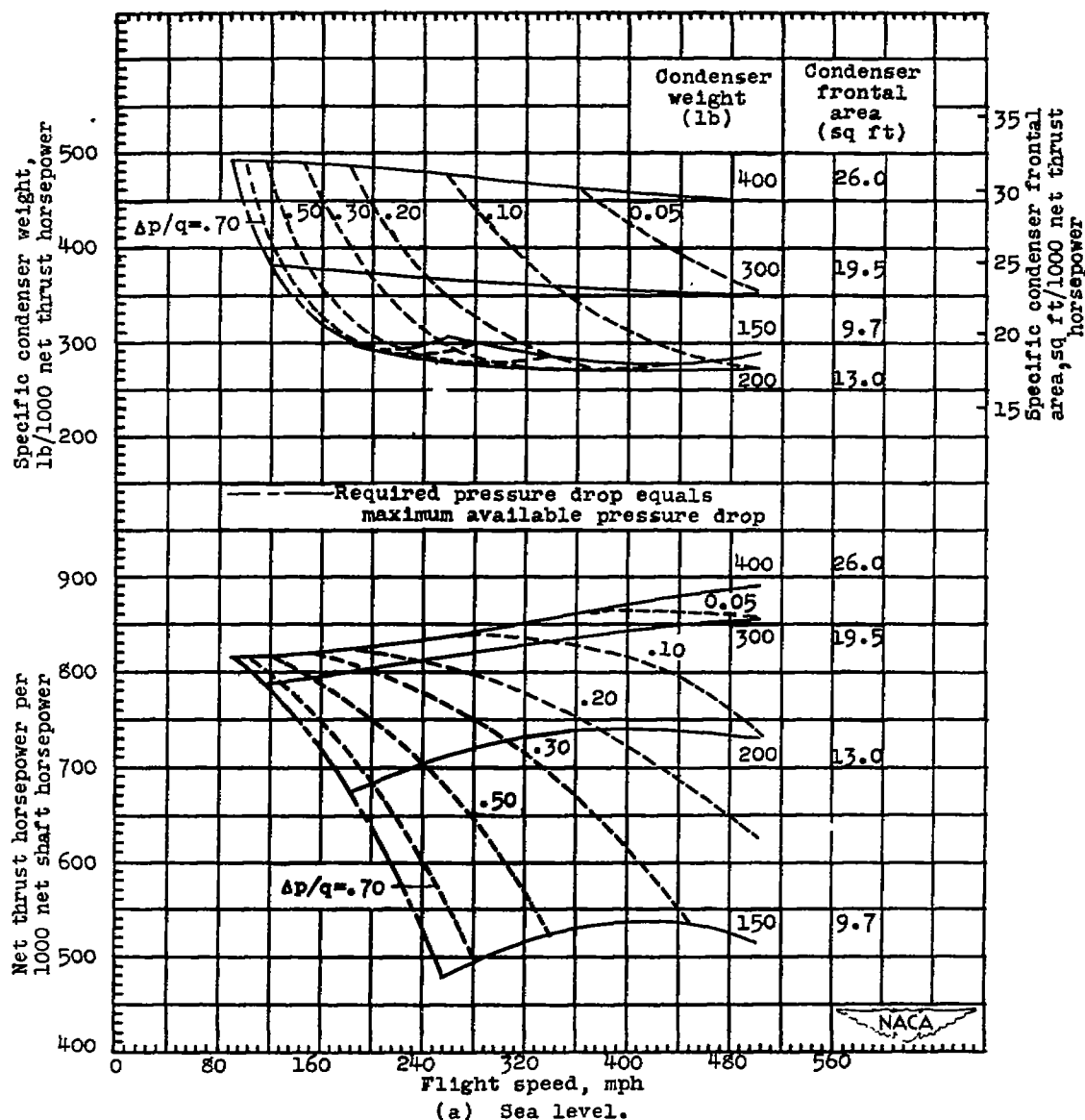power, 1000 horsepower; turbine and propeller efficiencies, 0.85;
saturated steam at turbine outlet.

(c) $\Delta p/q$, 0.60.
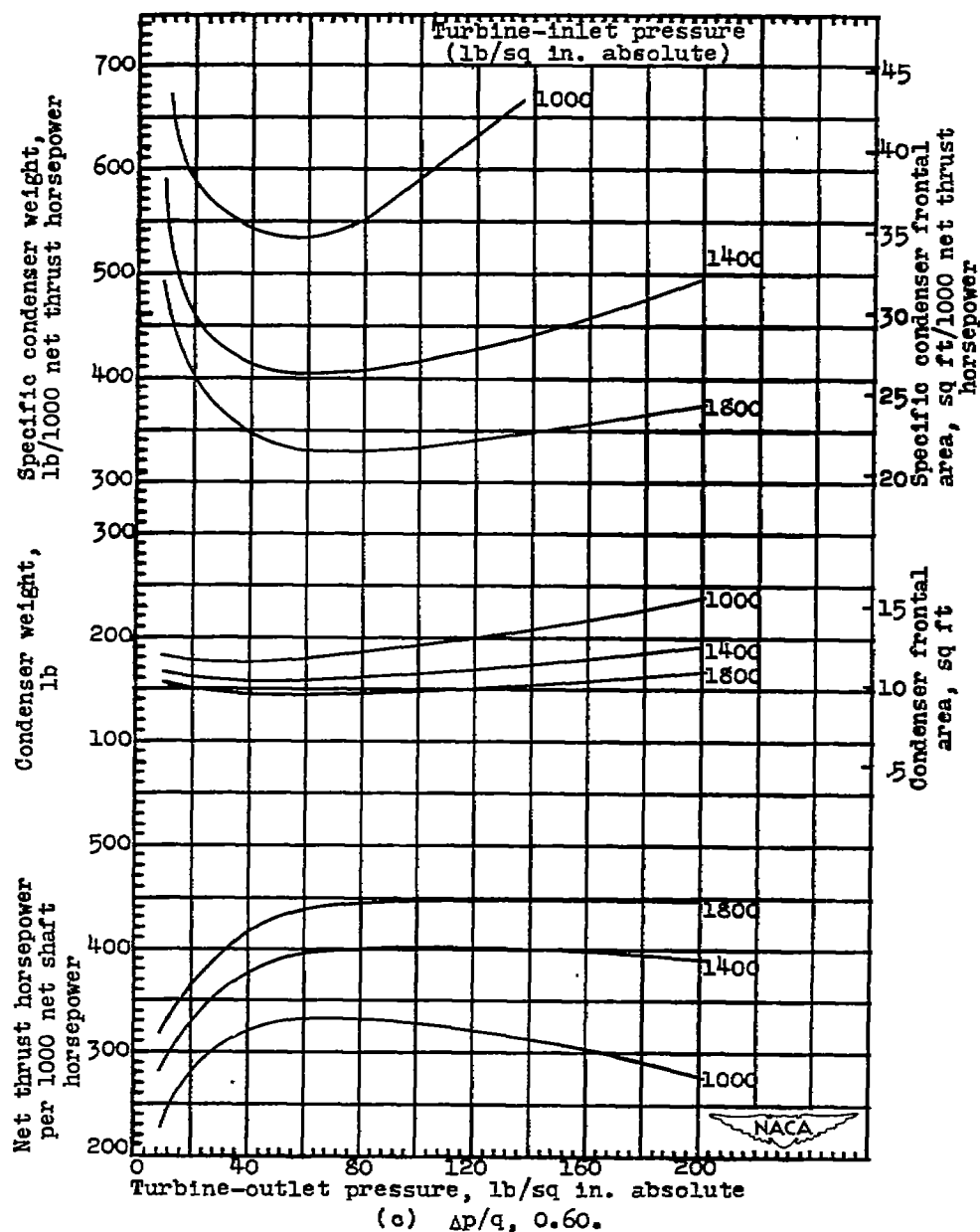
Figure 3. — Concluded. Variation of net thrust horsepower, condenser
   weight and frontal area, and specific condenser weight and frontal
   area with turbine—outlet pressure for three turbine—inlet pressures.
   Flight speed, 500 miles per hour; altitude, 30,000 feet; turbine
   power, 1000 horsepower; turbine and propeller efficiencies, 0.85;
   saturated steam at turbine outlet.
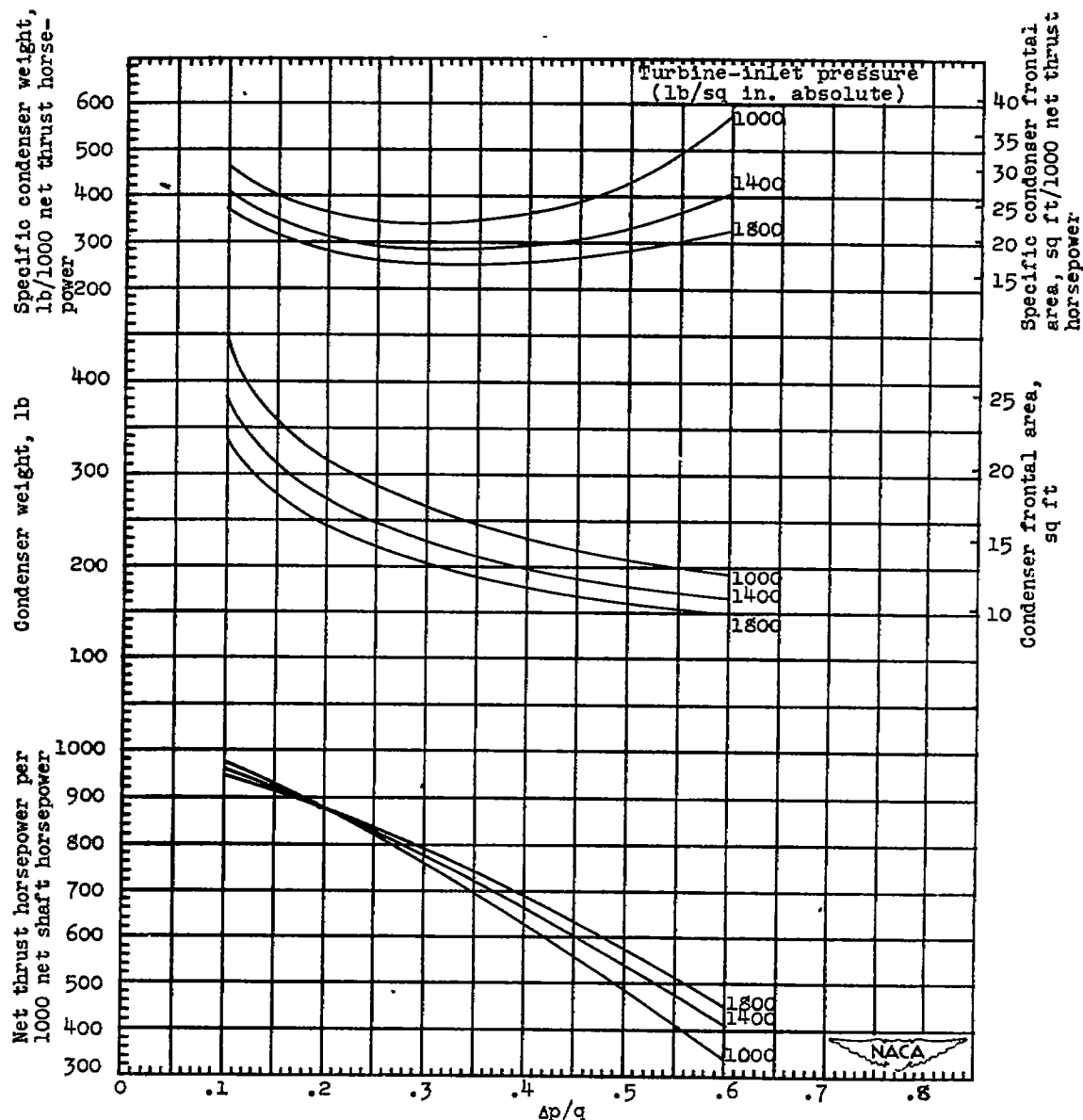
Figure 4. — Variation of net thrust horsepower, condenser weight and
  frontal area, and specific condenser weight and frontal area with
  Δp/q for three turbine—inlet pressures. Turbine—outlet pressure,
  100 pounds per square inch absolute; flight speed, 500 miles per hour;
  altitude, 30,000 feet; turbine power, 1000 horsepower; turbine and
  propeller efficiencies, 0.85; saturated steam at turbine outlet.

Figure 5. — Variation of net thrust horsepower, condenser weight and frontal area, and specific condenser weight and frontal area with turbine-inlet temperature. Turbine-inlet pressure, 1400 pounds per square inch absolute; turbine-outlet pressure, 100 pounds per square inch absolute; Δp/q, 0.30; flight speed, 500 miles per hour; altitude, 30,000 feet; turbine power, 1000 horsepower; turbine and propeller efficiencies, 0.85.

Figure 6. — Variation of net thrust horsepower and specific condenser
weight and frontal area with flight speed for various condenser weights
and frontal areas. Turbine-inlet pressure, 1400 pounds per square inch
absolute; turbine-outlet pressure, 100 pounds per square inch absolute;
turbine-inlet temperature, 866° F; turbine power, 1000 horsepower;
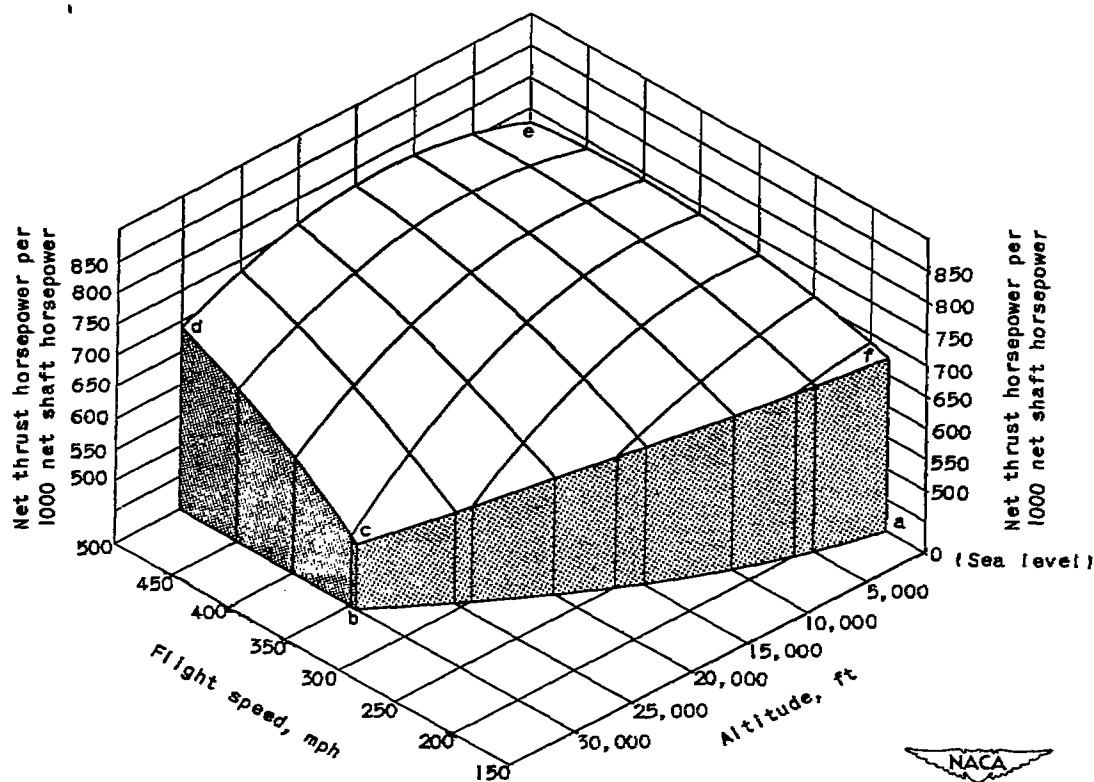turbine and propeller efficiencies, 0.85.
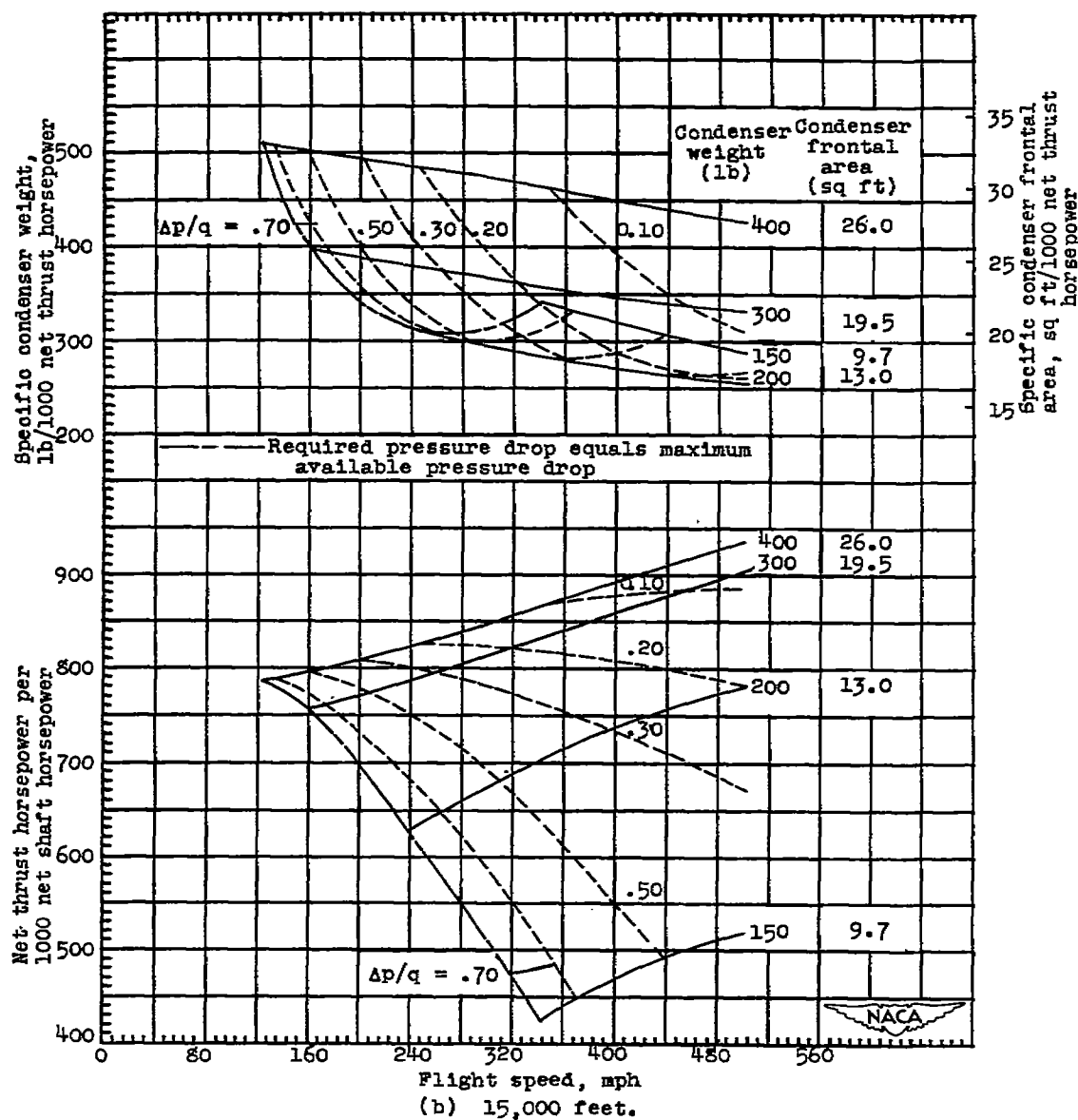
Figure 6. — Continued. Variation of net thrust horsepower and specific condenser weight and frontal area with flight speed for various condenser weights and frontal areas. Turbine—inlet pressure, 1400 pounds per square inch absolute; turbine—outlet pressure, 100 pounds per square inch absolute; turbine—inlet temperature 866° F; turbine power, 1000 horsepower; turbine and propeller efficiencies, 0.85.
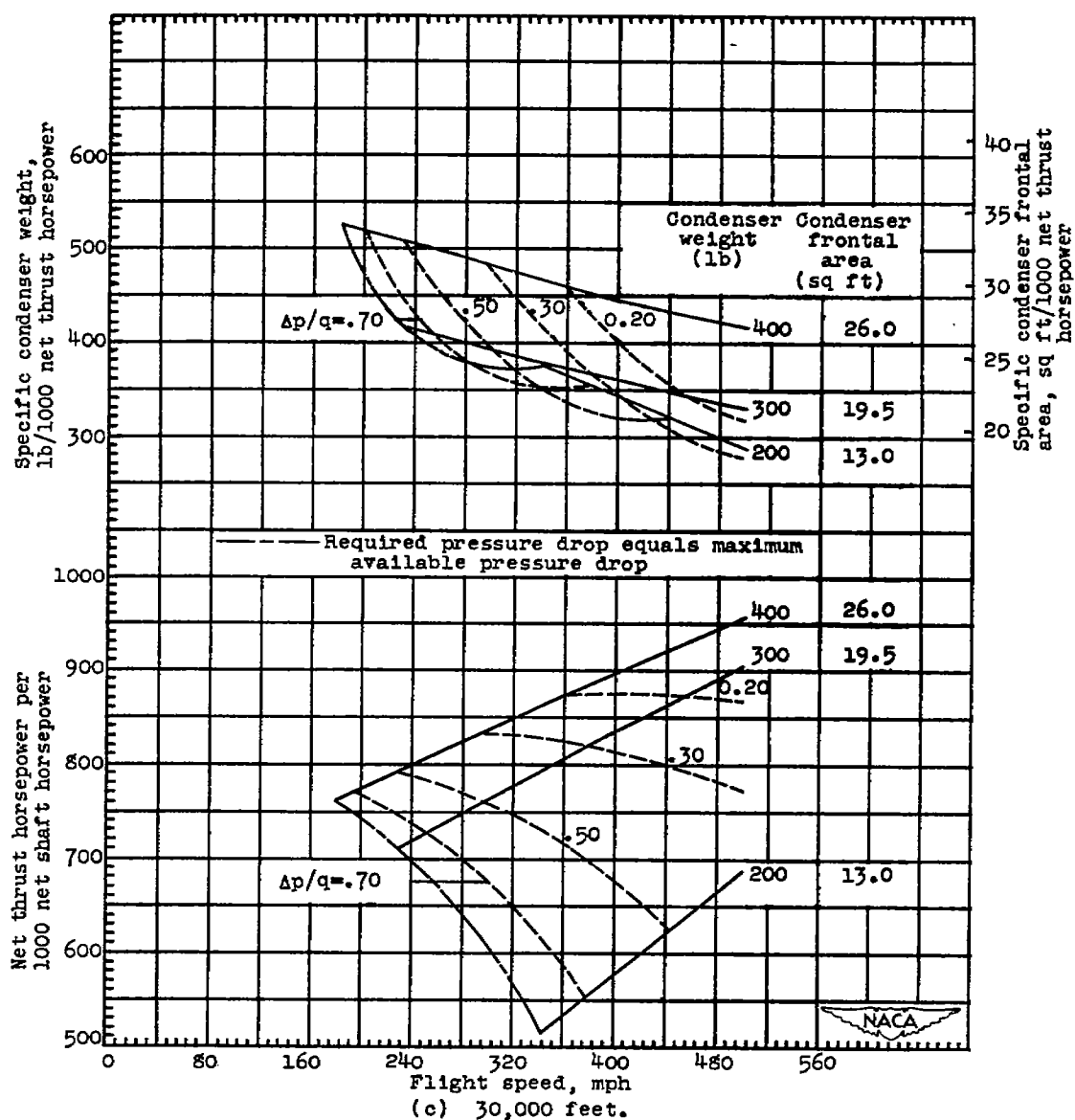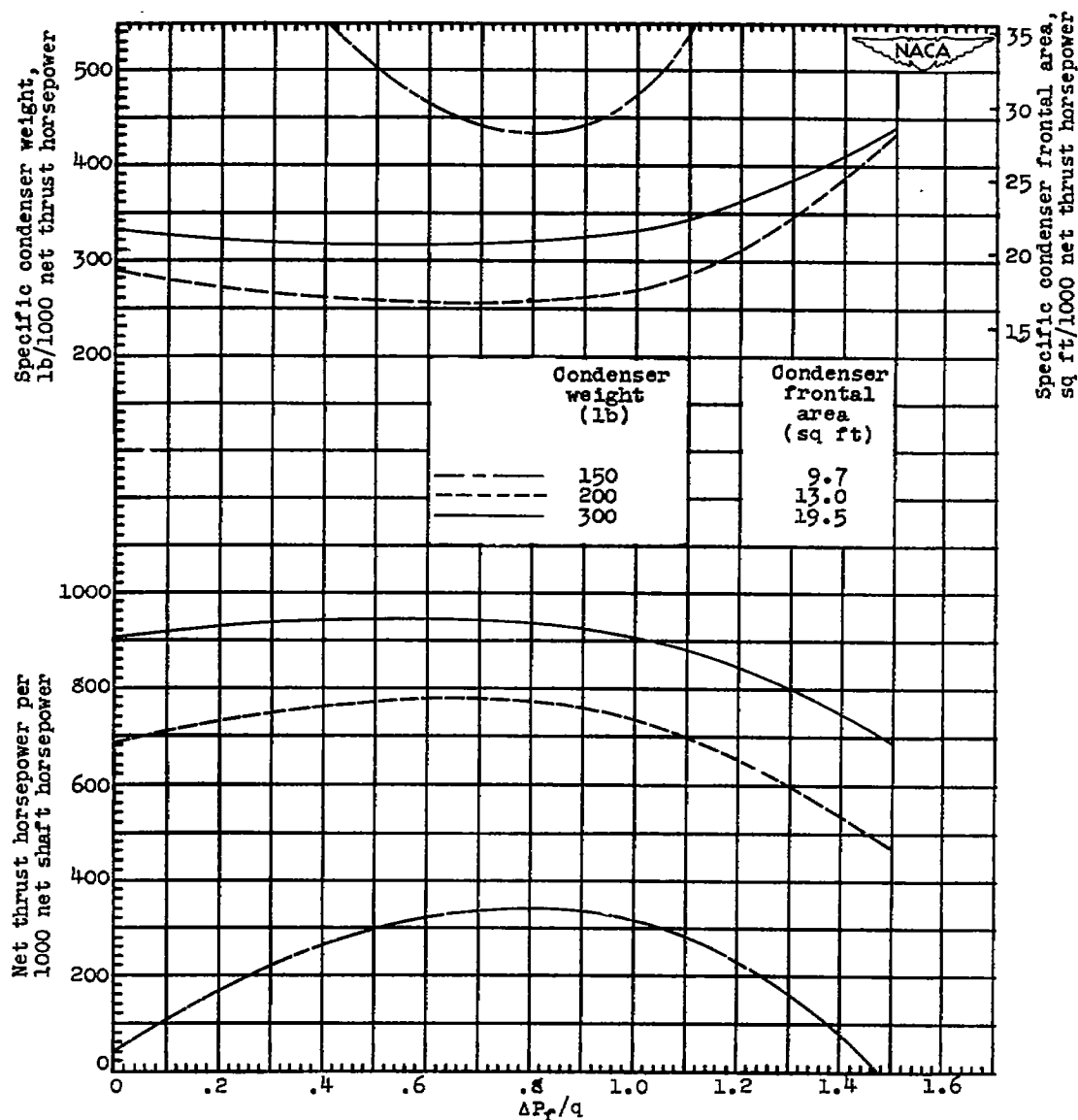
Figure 6. — Concluded. Variation of net thrust horsepower and specific
condenser weight and frontal area with flight speed for various con-
denser weights and frontal areas. Turbine—inlet pressure, 1400 pounds
per square inch absolute; turbine—outlet pressure, 100 pounds per
square inch absolute; turbine—inlet temperature, 866° F; turbine
power, 1000 horsepower; turbine and propeller efficiencies, 0.85.

Figure 7. — Variation of net thrust horsepower with flight speed and
altitude for condenser having weight of 200 pounds and frontal area of
13.0 square feet. Turbine—inlet pressure, 1400 pounds per square inch
absolute; turbine—outlet pressure, 100 pounds per square inch absolute;
turbine—inlet temperature, 866° F; turbine power, 1000 horsepower; tur-
bine and propeller efficiencies, 0.85.

Figure 8. — Variation of net thrust horsepower and specific condenser weight and frontal area with $\Delta P_f/q$ for three condenser weights and frontal areas. Turbine—inlet pressure, 1400 pounds per square inch absolute; turbine—outlet pressure, 100 pounds per square inch absolute; turbine—inlet temperature, 866° F; flight speed, 500 miles per hour; altitude, 30,000 feet; turbine power, 1000 horsepower; turbine, propeller, and fan efficiencies, 0.85.

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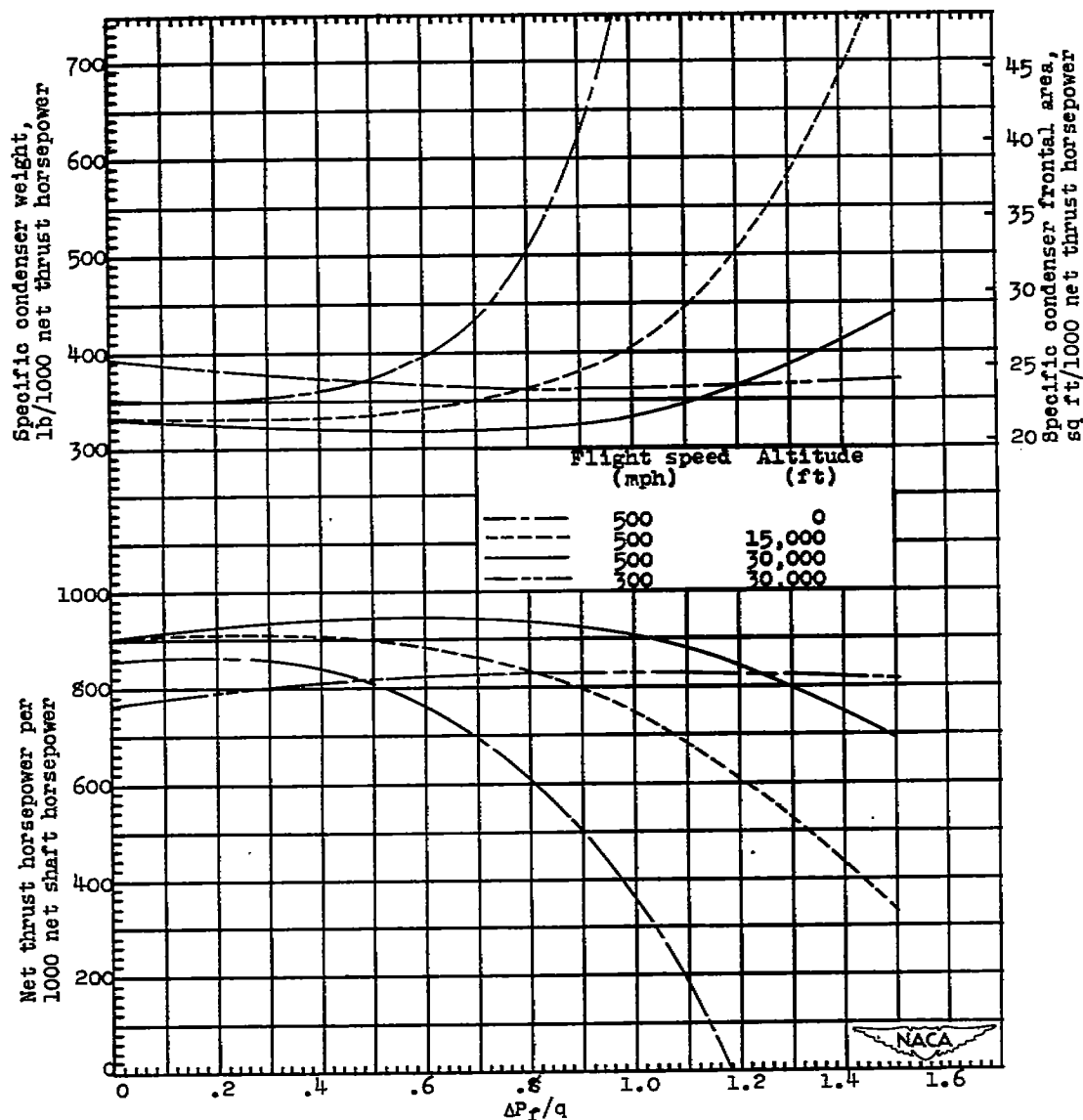
Figure 9. — Variation of net thrust horsepower and specific condenser
weight and frontal area with $\Delta P_f/q$ at various flight speeds and
altitudes. Condenser weight, 300 pounds; condenser frontal area,
19.5 square feet; turbine–inlet pressure, 1400 pounds per square inch
absolute; turbine–outlet pressure, 100 pounds per square inch abso-
lute; turbine–inlet temperature, 866° F; turbine power, 1000 horse-
power; turbine, propeller and fan efficiencies, 0.85.
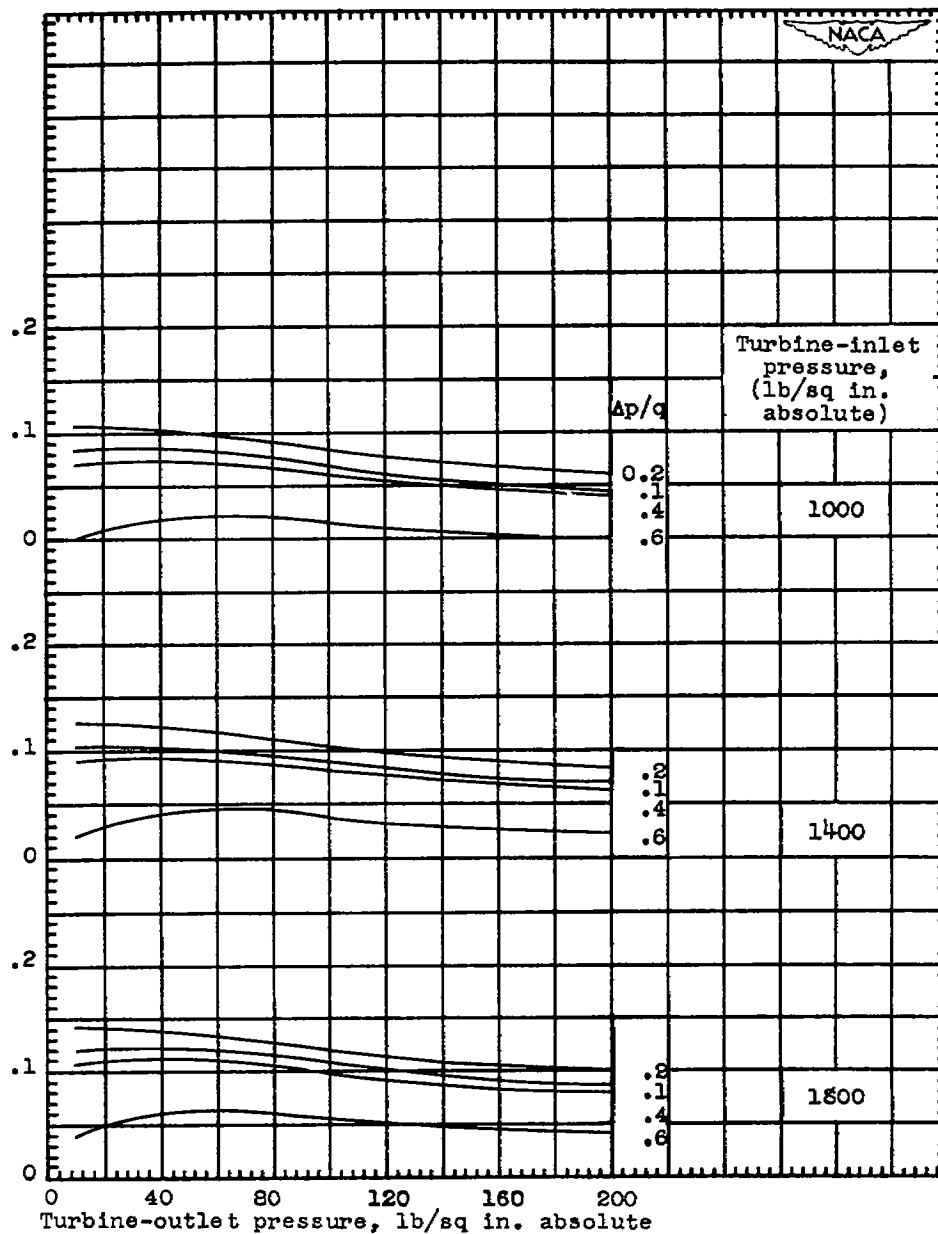
Figure 10. — Variation of over—all efficiency with turbine—outlet pres-
sure for various turbine—inlet pressures and values of Δp/q. Flight
speed, 500 miles per hour; altitude, 30,000 feet; turbine and propel-
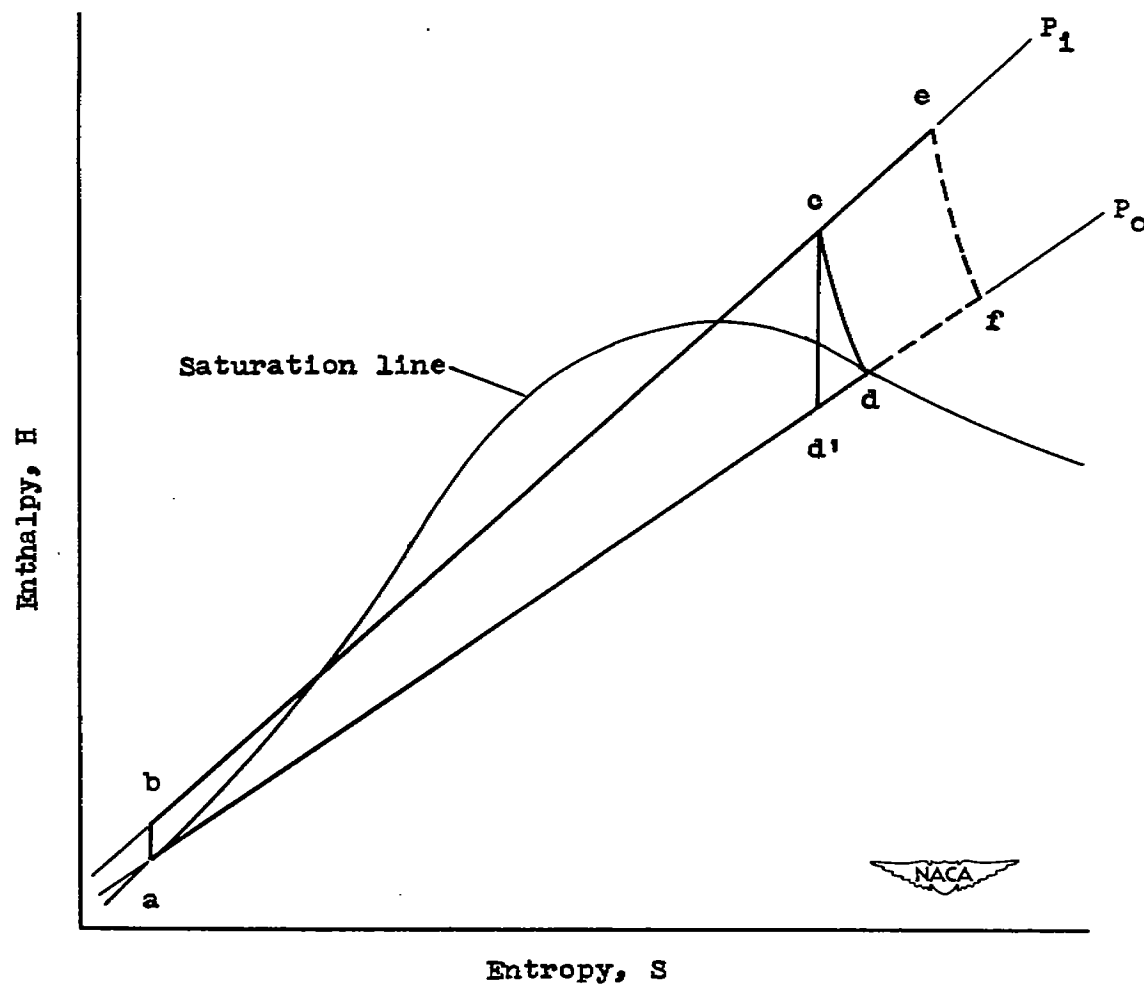ler efficiencies, 0.85; saturated steam at turbine outlet.
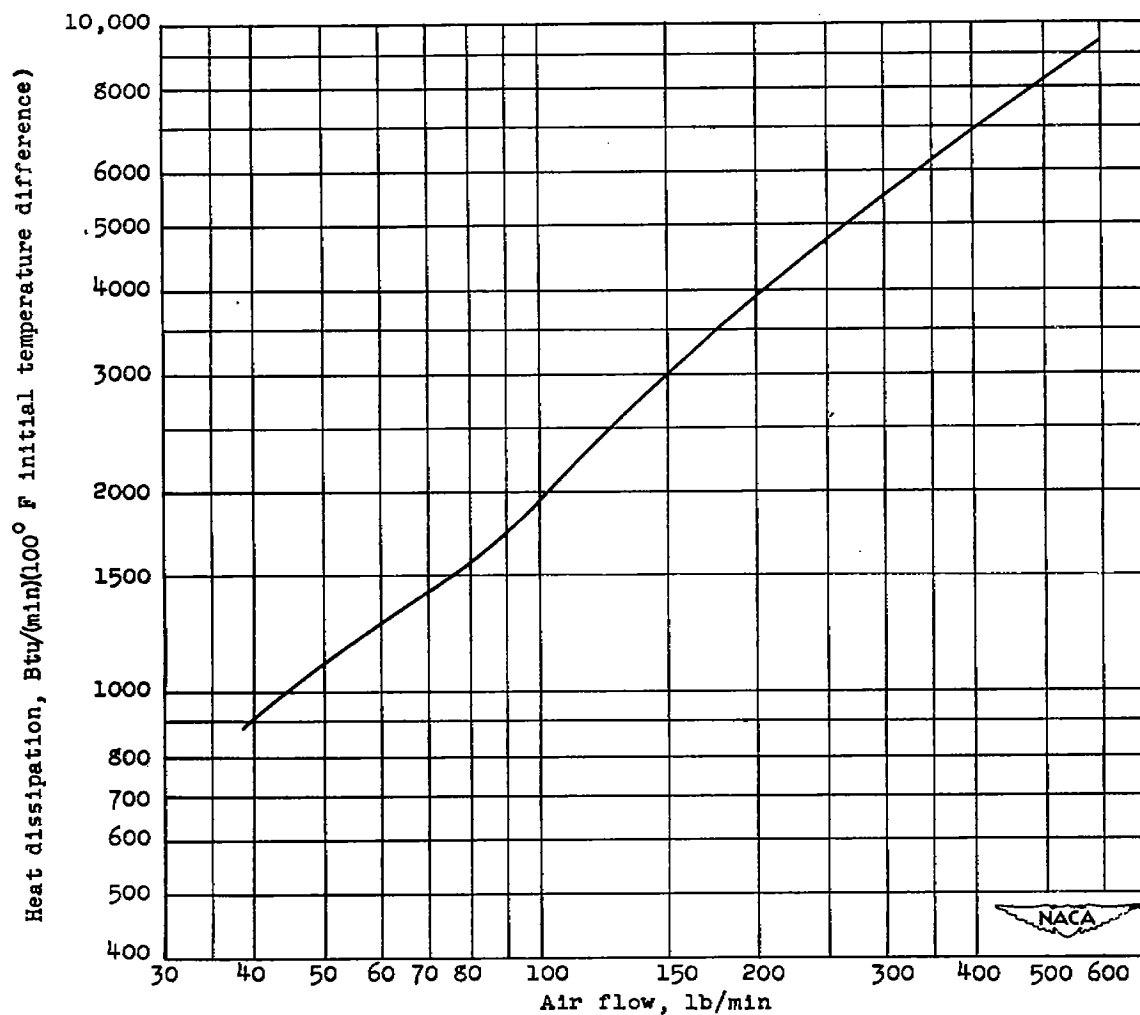
Figure II. — Schematic diagram of steam cycle.

Figure 12. — Variation of heat dissipation with cooling—air flow for a condenser having a frontal area of 1 square foot.
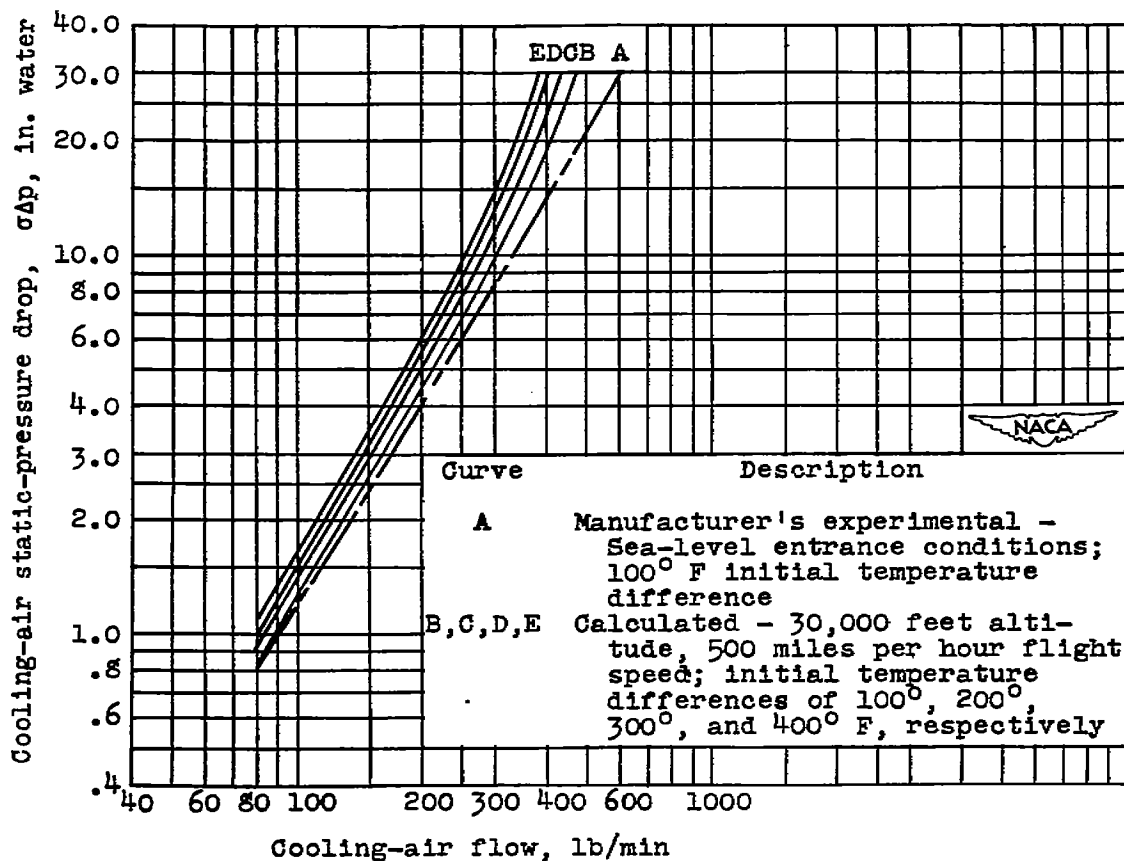
Figure 13. — Variation of cooling-air pressure drop with cooling-air flow for a condenser having a frontal area of I square foot.
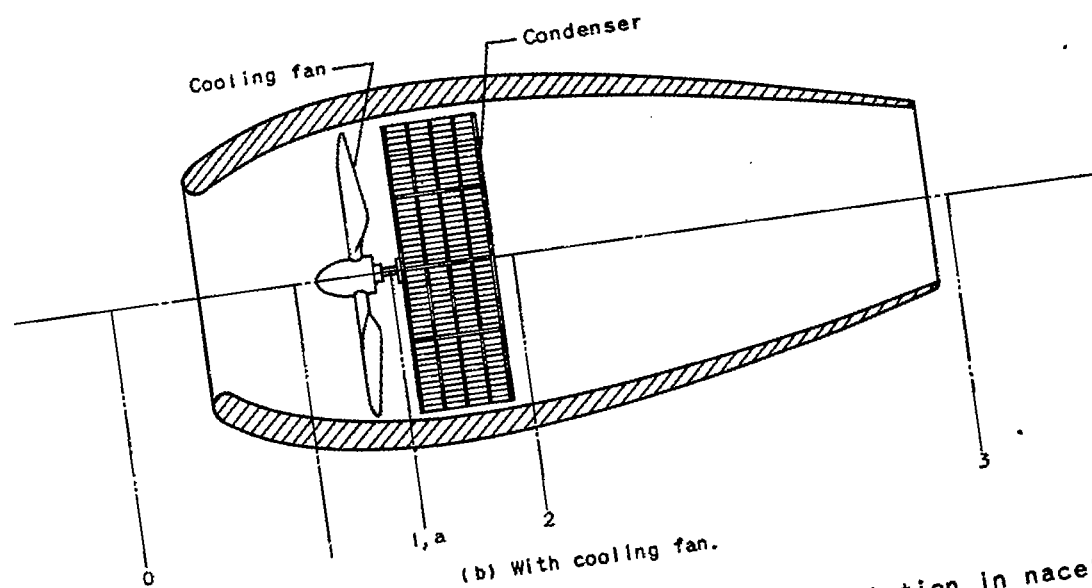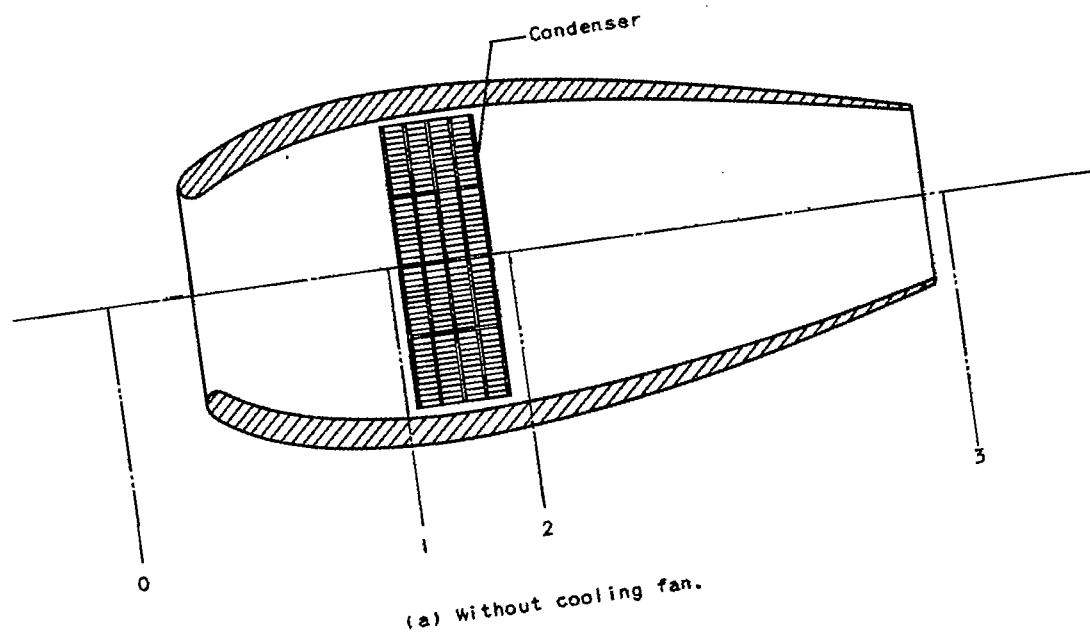
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Condenser

(a) Without cooling fan.

NACA

Cooling fan

Condenser

(b) With cooling fan.

Figure 14. — Schematic diagrams of condenser installation in nacelle.